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DEPARTMENT OF COMMERCE

UNITED STATES BUREAU OF MINES
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PETROLEUM AND NATURAL-GAS STUDIES OF THE UNITED STATES BUREAU OF MINES

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H. C. Fowler

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DEPARTMENT OF COMMERCE - BUREAU OF MINES

PETROLEUM AND NATURAL-GAS STUDIES OF THE UNITED STATES BUREAU OF MINES[1]

By H. C. Fowler[2]

The social economy, or public interest, and national defense require wise development and efficient use of the oil and gas resources of the United States. In this development and use, and in the prevention of economic and physical waste of oil and gas, the objectives of the petroleum and natural-gas industries, the Government (Federal, State, and local), and the public are the same. Differences of viewpoint generally have originated in the failure of one of the triad to have a clear or complete understanding of the motives behind the activities of the other component groups or full knowledge of what each is trying to accomplish.

The United States Bureau of Mines through its petroleum and natural-gas division makes technologic and scientific investigations pertaining to recovery,[3] preparation, refining, and use of oil and natural gas with the view of reducing waste, increasing safety and efficiency, and aiding economic development.

Frequently questions are asked regarding the purpose and scope of studies made and the results obtained by the Bureau of Mines on technical problems pertaining to petroleum and natural gas. In order that there may be available authentic information as to methods whereby the Bureau of Mines is functioning to the benefit of the oil and gas industries, the Government, and the public, and to the better coordination of thought on the part of these groups, this paper has been written. For a clearer understanding, a brief review is first given of the Bureau's earlier work on oil and gas, to show the types of problems studied and the research procedure that has been followed; also, there are indicated the changes in the scope of activities of the petroleum and natural-gas division that have taken place within the last 18 years concurrent with a magnitude of development of the oil and gas industries that finds but few equals. In the latter part of the paper close scrutiny is given to present specific studies on oil and gas and the results that are being obtained.

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[1] The Bureau of Mines will welcome the reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from U. S. Bureau of Mines Information Circular 6737."

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[3] The meaning here conveyed is in accordance with somewhat common usage in the petroleum and natural gas industries - namely, the withdrawal of oil and gas from underground reservoirs by various production methods - rather than in accordance with the more exact definition of regaining that which has been lost.

The Bureau of Mines Function Pertaining to Petroleum and Natural Gas

It has been a motivating thought within the Bureau of Mines since its petroleum division became an officially recognized unit of the Bureau on July 1, 1914, that the chief function of that division is to develop and carry out a coordinated system of research projects pertaining to oil and gas. In performing this function, the best available knowledge and information regarding physical phenomena and other conditions are gathered together, and analyses are made of the data that help to explain the working out of definite laws and fundamental relationships. By the practical application of these relationships to oil and gas fields, pipe lines, and refineries, it is possible to produce oil and gas more rationally, transport them more efficiently, and manufacture them into useful products with less cost.

The Bureau has long recognized that there is a merging from fundamental research in the laboratory to so-called "practical" research. Therefore, in developing the philosophy of any research project it is not enough to establish certain fundamental relationships by laboratory experiment: to be effective the work must have practical application in the field or at the plant.

Through its publications, letters, formal papers, personal discussions, and other means of disseminating information, the Bureau also is slowly yet definitely helping to guide the public mind away from erroneous ideas (evolved during the early life of the petroleum industry because of the fluid and mobile characteristics of oil and gas) to those on a more rational basis, that tend to conform more nearly with the unalterable laws of nature.

Early Work on Oil and Gas

It is significant that many of the early pronouncements and methods of the petroleum engineers of the Bureau of Mines are only now being recognized generally throughout the industry and by the public. In reference to what should constitute adequate legislation for the protection of oil and natural-gas resources, for example, the Bureau of Mines, in 1915, after meetings were held with various State agencies, made the following statement:[4]

> The laws not only protect against waste but also insure a market for natural gas, and thus induce producers to conserve gas instead of allowing it to escape, a rateable marketing of all oil and natural gas offered for sale being provided for. In case production becomes too large for the available transportation and marketing facilities, the transportation facilities must be increased or the oil and gas must be confined until they can be utilized. This provision will prevent large quantities of oil and natural gas from being brought to the surface and stored with a resulting waste of gas and a lowering of oil prices.

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[4] Fifth Annual Report of the Director of the Bureau of Mines to the Secretary of the Interior for the fiscal year ended June 30, 1915, p. 80.

The foregoing statement reflects what many students of oil and gas conservation believe is the essence of a rational conservation law today.

Another example of a forward-looking viewpoint pertaining to petroleum technology may be found in a series of experiments performed by the Bureau of Mines more than 10 years ago, giving a visible demonstration of the migratory tendencies of gas, oil, and water in the reservoir. The experiments[5] were not carried out in their entirety, but the technique was developed and certain fundamental relationships established which have had wide and definite application, particularly since the water conditions in the East Texas field and elsewhere have become such an important problem to operators, to regulatory bodies, and to the courts of law.

During the first year of its organization (1910-1911), the Bureau of Mines analyzed samples of petroleum (continuing work started by Allen and his associates in the technologic branch of the United States Geological Survey before the Bureau was created) in its fuel-testing laboratory at Pittsburgh, Pa., and a small laboratory was maintained in the Custom House at San Francisco for the purpose of analyzing fuel oils used by the Government. Also, a method of analyzing natural gas (not fundamentally different from the method in general use today) was developed by Burrell and others.[6] Work on various oil and gas problems was continued during the second fiscal year, and during the third fiscal year nearly 150 samples of natural gas were collected and analyzed in a study of the composition of natural gas in different parts of the country. Possibilities of extracting gasoline from natural gas also were studied. Realizing that wastes of oil and gas were occurring on public lands and lands adjacent thereto, some field studies were made, particularly in California, with reference to excluding water from wells by the use of cement.

The need of specifications for petroleum products used by the Government is indicated in the early correspondence of the Bureau of Mines. Joseph A. Holmes, first director of the Bureau of Mines, wrote to a large number of scientific and technical men under date of July 15, 1912, pointing out the wide difference of opinion among manufacturers and consumers of petroleum products in regard to proper specifications. Subsequently, Dr. Holmes suggested an attempt to coordinate and organize "inquiries of national scope through which knowledge in the possession of different investigators could be made available for the general good." A series of conferences, held at Pittsburgh, Pa., in August and September, 1913, was attended by representatives of 34 organizations. Many problems of the petroleum industry, in addition to specifications for petroleum products, were discussed.

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[5] Mills, R. Van A., Experimental Studies of Subsurface Relationships in Oil and Gas Fields: Econ. Geol., vol. 15, 1920, pp. 398-421; Relations of Texture and Bedding to the Movements of Oil and Water Through Sands: Econ. Geol., vol. 16, 1921, pp. 124-141.

[6] Later reported in Bulletin 197, Bureau of Mines; latest edition published in 1926.

As an outgrowth of those conferences, plans were considered seriously for the organization of what was termed "The American Petroleum Society,"[7] but probably the greatest general good that came out of those meetings was the realization, definitely stated, that "the industry is groping in the dark and that little accurate or even general information is available."

In 1914, the capital invested in petroleum in the United States was said to be about one-half billion dollars, and wastes in drilling, development, storage, and transportation were estimated to be at least $50,000,000 per annum, a large part of which was preventable. Recognizing the condition, the Bureau of Mines started an active conservation campaign, especially stressing the need for the prevention of gas wastage. Corrective measures recommended by the Bureau led, in a short time, to the saving of 350,000,000 cubic feet per day of actually measured open-flow waste of gas. A study also was begun of the decline of oil wells, which later developed into one of the major, if not epic, contributions to the advancement of petroleum technology, and methods were suggested for prolonging the producing life of wells. In transportation, work was directed to efficient methods of construction and operation of pipe lines, cost studies of such methods and operation, and to various types of tank and reservoir construction.

The publication of a report on the physical and chemical properties of petroleums of California[8] was the beginning of a general study of various oils to determine their relative values as sources of commercial products. These crude-oil surveys now include samples from nearly all of the important fields in the Western Hemisphere and from many of the more important fields in the Eastern Hemisphere.

Because very little scientific knowledge of chemistry involved in refining petroleums was available, and most refiners were dependent upon knowledge gained by their apprenticeship to older refiners, studies of refinery technology were started by the Bureau with the view of developing more efficient methods for the preparation of petroleum products.

In those early formative years of the petroleum division of the Bureau of Mines, the whole broad field of engineering and scientific research confronted the small group of technologists who first constituted this division. The insight with which an urgent need was sensed for broad and fundamental studies pertaining to petroleum and allied substances is reflected in the titles and subject matter of many of the earlier publications of the Bureau of Mines, many of which remain today standard references on the subject of petroleum technology.

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[7] Explained in detail in Technical Paper 72, Bureau of Mines, 1914. (Out of print.)

[8] Allen, I. C., and Jacobs, W. A., Physical and Chemical Properties of the Petroleums of the San Joaquin Valley, Calif.: Bull. 19, Bureau of Mines, 1911, 60 pp.

During the first years of the petroleum division of the Bureau of Mines, there were few petroleum technologists in the employ of the oil companies, and in addition to their basic studies, engineers of the Bureau were called upon to render all manner of service to the companies, frequently taking direct charge of the work, with the consent of the operators, in an effort to bring about corrective measures or improved methods. For example, the Bureau was the pioneer in advocating uniform casing programs and the cementing of wells, and by work on the derrick floor, the use of peg models, cross sections, and other devices, operators were gradually convinced of the harmful effects of drilling into oil-producing formations without adequate safeguards against water encroachment.

It was during this period, when "in the consensus of opinion of well-informed authorities" demand for petroleum likely would soon exceed the productive capacity of the then discovered reserves, that the Bureau of Mines gave to the industry the basic and studied report of Lewis,[9] which laid the ground work for later research and extensive practical application of methods for recovering increased amounts of petroleum from the underground reservoirs.

During the late part of 1917 and throughout 1918, the activities of the Bureau of Mines on petroleum and natural gas were devoted in large measure to problems of the war. The personnel of the petroleum division, because of their training and their knowledge of oil and gas matters, were in a position to give immediate service to the newly created United States Fuel Administration and to the armed forces of the country. Throughout the war-time period, in addition to the performance of a variety of confidential technical work, a determined effort was made to emphasize the prevention of waste of oil and gas, and their more efficient utilization.[10]

At the end of the war "the Bureau was confronted with the need of enabling the mineral industries of the country to meet most effectively the inevitable difficulties that would confront them during the transition from the strain of war to the resumption of the normal activities of peace. Investigations in progress were stopped or given a new direction; plans for the future were changed; new investigations were proposed; work was concentrated on those investigations that promised to be most beneficial to the mineral industries during the period of transition and readjustment."[11]

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[9] Lewis, J. O., Methods for Increasing the Recovery from Oil Sands: Bull. 148, Bureau of Mines, October 1917, 128 pp.

[10] A summarized report of this work is given in Bureau of Mines Bull. 178-C, War Work of the Bureau of Mines: Petroleum Investigations and Production of Helium: June 1919, pp. 63-88 (out of print).

[11] Ninth Annual Report of the Director of the Bureau of Mines for the fiscal year ended June 30, 1919, p. 9.

As examples of peace-time activities, immediately following the war, the petroleum division of the Bureau evolved a new method for estimating the future and ultimate production of oil properties,[12] under the then existing practices of so-called "normal decline," and a comprehensive study of underground conditions in oil fields resulted in a publication[13] on that subject which is a continuing standard reference for all production engineers.

During this time also, as examples of the chemical studies, a widely recognized authoritative report was made on the quality of gasoline marketed in the United States,[14] and a system of analyzing crude oils was developed which is the basis for the Bureau's reports on its surveys of crude oils produced throughout the world.[15]

With the passage of the so-called "Leasing Act" of February 25, 1920, Bureau engineers prepared operating regulations for oil and gas leases under this act to protect Government lands against waste and damage in the development of oil and gas, and from March 3, 1921, to July 1, 1925 (on which date the Bureau of Mines was transferred from the Department of the Interior to the Department of Commerce), all supervisory and regulatory work pertaining to the drilling for and the production of oil and gas on public lands was vested in the Bureau of Mines.

Growth of the Industry

The petroleum industry has developed its capital investment from the one-half billion dollars, reported for 1914, to a total in 1932 reported to be 12 billion dollars. Concurrently, the natural-gas industry has grown from the status of an almost unwanted appendage of the oil industry to a self-supporting business of national importance. In 1930, the natural-gas industry was conservatively estimated to have expended $500,000,000 for expansion alone; and in 1931, through its transmission lines (some extending 1000 miles or more across the country) it delivered gas valued at $392,816,000 at points of consumption. Although there was an appreciable indicated decline in consumption for 1932, the estimated value for that year was well over $350,000,000.

During this epoch, the problems of oil and gas have changed. As some problems have been solved, many others have appeared and the whole economic and technical structure of the oil and gas industries and the public interest therein have grown more complex.

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[12] Beal, Carl H., The Decline and Ultimate Production of Oil Wells, with notes on the Evaluation of Oil Properties: Bull. 177, Bureau of Mines, 1919, 215 pp. Later followed by Cutler, Willard W., Jr., Estimation of Underground Oil Reserves by Oil-Well Production Curves: Bull. 228, Bureau of Mines, 1924, 114 pp.

[13] Ambrose, A. W., Underground Conditions in Oil Fields: Bull. 195, Bureau of Mines, 1921, 238 pp.

[14] Hill, H. H., and Dean, E. W., Quality of Gasoline Marketed in the United States: Bull. 191, Bureau of Mines, 1920, 275 pp.

[15] Dean, E. W., Hill, H. H., Smith, N. A. C., and Jacobs, W. A., The Analytical Distillation of Petroleum and Its Products: Bull. 207, Bureau of Mines, 1922, 82 pp.

Changing Scope of Activities

Today engineers are confronted with questions regarding the economic as well as the physical conditions that are involved in drilling to and producing from deep-lying formations, which less than 10 years ago were only conjectured; the effect of production control on ultimate recovery; the interpretation of so-called "bottom-hole" or subsurface pressures; the amount of gas dissolved in the oil under reservoir conditions; the flow of oil and gas through the porous rocks of the reservoir and the related problems of well spacing; the many phases of unit operation and the gas-oil-energy attributes of the structures; the widespread production, distribution, and use of natural gas; the manufacture of motor fuels and lubricants by processes which had not been conceived of in 1914 and 1915; and the complications of the technical phases of taxation.

As the industry has changed through growth and expansion, so have the field of activities and some of the types of study of the Bureau of Mines changed. From the very natural result of the general dissemination of basic knowledge, the Bureau no longer is required actually to tutor by personal instruction in the technique of oil and gas production in the same manner as in former years. Technical institutions and universities have developed courses in petroleum technology with the result that an increasing number of graduate engineers, who have specialized in oil and gas studies, have been available for employment by the oil and gas companies. Also, many former Bureau of Mines engineers have accepted responsible positions in the petroleum and natural-gas industries and have done much to implant the principles of good engineering and scientific thought as applied to petroleum and natural gas in the organizations which they now serve. Many companies have their own research organizations, both in the laboratory and in the field, and some types of laboratory research are conducted at universities and other technical institutions.

Recognizing this growth and change, the Bureau of Mines for several years has concentrated its efforts on studies of a fundamental nature that apply throughout the whole industry and that can not reasonably be made by individual companies or others. In so doing it is closely following the policy established 18 years ago to do pioneer work on problems that have broad, if not national or international, significance. Some of the early problems were so fundamental that the general plan of attack has not radically changed. These researches of the continuous type should be perpetuated in order to accumulate the knowledge that is required for proper functioning of the industry.

This period of change in some major activities of the Bureau was perhaps first definitely evidenced when in 1926 the oil-recovery laboratory at the Petroleum Experiment Station, Bartlesville, Okla., was organized with a working program and outline of procedure as definite as any basic research project will permit, and the former practice of having one or more expert drillers in the field was discontinued shortly thereafter.

A research project which requires the development of a philosophy is never undertaken by the Bureau until a careful canvass of its need has been made. For example, several years of planning preceded the establishment of the oil-recovery laboratory as the nucleus of a definite project. Again, before work was started to determine the amount and character of gas dissolved in oil in natural reservoirs, personal discussion or correspondence was held with representative engineers in all parts of the country in order to obtain their views regarding the need for such work. Conversely, when a problem reaches a state of completion where sufficient data have been compiled to enable the industry to make practical application of the results, a report of the findings is written for general distribution, and active work on the problem is suspended. This procedure was typically true of the problem of cementing wells, when some years ago it became evident that the industry had accepted the results of findings of the Bureau on that subject and was using them effectively to protect against underground waste of oil and gas and was amplifying the technique as occasion demanded, due to peculiar local conditions or new developments. However, current information on suspended problems is gathered and kept on file for use as needed in the general dissemination of information or for revision of earlier published work.

Facilities for Study

At the present time (May 1933) the petroleum and natural-gas division of the Bureau of Mines has a staff of approximately 50 technical men and a small force of clerks, mechanics, and skilled laborers. Headquarters for fieldwork are maintained at the Petroleum Experiment Station, Bartlesville, Okla., and at the petroleum field offices at San Francisco, Calif., Dallas, Tex., and Laramie, Wyo.

The Petroleum Experiment Station was established in 1917 upon a site containing 5 acres of land given by G. B. Keeler of Bartlesville. Two brick buildings, one an administration and office building and the other a chemical laboratory, were erected through the efforts of the Chamber of Commerce of Bartlesville, Okla., in providing $50,000 for that purpose. During the life of the station, the State of Oklahoma has generously contributed cooperative funds to aid in its maintenance and operation and for the conduct of oil and gas investigations which pertain more specifically to the industry of that State. Various other studies on relatively "short-time" problems have been conducted at the Petroleum Experiment Station and at the petroleum field offices under the Bureau's organic provision which enables it to enter into formal cooperative agreements with agencies that are interested in technologic advancement in the mineral industries.

The San Francisco office has been maintained since the Bureau of Mines was organized in 1910. At first it was primarily a field laboratory where fuel oils, purchased by the Federal Government, were tested. Later, as the interest in petroleum technology grew more pronounced, the San Francisco office became the western center of the Bureau of Mines on all matters pertaining to oil and gas. Phases of the Bureau's petroleum research projects under study at San Francisco will be discussed later in the paper.

The Dallas (Tex.) office was opened early in January 1920. The Dallas Chamber of Commerce was instrumental in bringing about the final selection of that city as the headquarters for petroleum engineers of the Bureau of Mines making studies in the oil fields of Texas, Louisiana, and Arkansas. The engineering field studies, made by the Dallas office of typical fields in all parts of the Gulf-Southwest, are related definitely to the production - research projects being conducted at the Bartlesville Station and at the other field offices.

The Bureau's work at the Laramie, Wyo., office began July 1, 1924, at the request of the Rocky Mountain operators and the State of Wyoming. The initial work there was devoted almost exclusively to production problems. With the completion and publication of the results of a study dealing with paraffin and congealing oil, interspersed with many shorter reports, the Bureau suspended active work on production problems at that office, and in January 1930 the personnel began a chemical and refining study to evaluate the future economic importance and refining values of the black oils of the Rocky Mountains.

This change in type of work was decided upon only after a thorough personal canvass of the changed conditions in the Rocky Mountain area clearly indicated to the Bureau that production problems were becoming progressively less important, and that the black-oil resources were a growing factor in the economic welfare of the region. The relation of this work to other refinery problems of the Bureau will be discussed further on in the paper.

Interrelationship of Research Problems

In the earlier work of the division, investigations were grouped under the three general headings of petroleum technology, chemical technology, and engineering technology, but the individual engineers and scientists worked more or less independently of each other. Correlation was maintained through the office of the chief petroleum technologist, and every man assisted his associates by constructive criticism of manuscripts and reports. This system proved to be successful and has led to the frequent statement that Bureau of Mines reports are among the most critically reviewed pieces of writing that appear in the technical literature. Because of the wide scope of his own problem and the many subjects theretofore untreated, it was logical that each man should follow his own course in collecting data and putting the results of his findings into published form where they could be referred to and used. The result is reflected by the nearly 500 publications on oil and gas that have been issued by the Bureau of Mines. This number does not include the many papers given before technical and other societies and specially prepared articles printed in the technical press.

The interrelationship of the several problems, however, both in refining and production, has been sensed for several years. This condition was evidenced first in reference to the chemical work, and after the petroleum laboratory was transferred from Pittsburgh, Pa., to Bartlesville, Okla., in 1923, the chief of the chemical section at the Bartlesville station served as supervising chemist for the whole division, devoting much of his effort to coordinating the problems then under study. In 1930, changed conditions showed the need for even closer correlation, and definite steps were taken to establish a direct and unified supervision of all work of the division dealing with petroleum chemistry and chemical engineering as pertaining to the refining of oils.

As in the refinery work, a common fundamental relationship was proved to exist and to govern the problems relating to the production of oil and gas. During the last 3 years especially, the several production-research projects have been conducted in accordance with a definite plan whereby the engineers in charge of the several studies meet in frequent conference and discuss their interrelated and mutual problems.

This interrelation of research problems will be developed further as the several problems are discussed.

Problems

For convenient treatment, the technical problems of the Bureau of Mines, pertaining to oil and gas, are discussed in the following pages under four general groups: (1) Petroleum chemistry and refining; (2) production of gas and oil, including related problems of pipe-line transportation of natural gas; (3) engineering field studies, and (4) special engineering problems.

(1) PETROLEUM CHEMISTRY AND REFINING

The major problem of the refinery section deals with sulphur compounds and other harmful substances in crude oils and their segregation and removal by better methods of fractionation and subsequent chemical treatment. To assure that the work in one laboratory would not be unnecessary duplication of work performed in the other laboratories but that each would supplement and augment the others, the supervising engineer at Laramie, Wyo., who is in direct charge of the studies of high-sulphur oils of the Rocky Mountains, is also held responsible for the progress of the work on refining the naphthene - base oils of California in the laboratory at San Francisco, Calif., and for the fractionation tests in visible distillation equipment and the other problems pertaining to sulphur in oils at the Bartlesville, Okla., station. Progress under this arrangement, since it was instituted in 1930, has proved the feasibility of the plan.

"Black Oils" of the Rocky Mountains

The study of the "black-oil" resources of Wyoming and the thermal-decomposition of Rocky Mountain high-sulphur crude oils is a phase of the major refinery project of the Bureau dealing with sulphur in petroleum.

The economic importance of this study to the whole Rocky Mountain area is clearly indicated by the fact that the production of light, low-sulphur crude oils in Wyoming has been decreasing since 1923. In 1930, the light-oil production about equalled the potential production of black oils, which a recent survey shows is between 36,000 and 46,000 barrels per day for wells already drilled. Actually, the black-oil production in 1932 was approximately 5,000 barrels per day. Unless new light-oil fields are discovered, more and more black oil must be refined to supply the regional demand for petroleum products.

The increasing importance of the black oils of the Rocky Mountains, as a source of refined products with which to meet a somewhat localized market, is evidenced by the activity of the Wyoming and Montana refiners in expanding their black-oil refining capacities during the latter part of 1932 and the first half of 1933.

The published conclusions so far developed in the study of high-sulphur crude oils of Wyoming are given in Bureau of Mines Technical Paper 538[16] (released October 25, 1932) as follows:

> The results of this survey indicate that most of the "gasoline and naphtha" fractions from Wyoming black oils, which constitute the portion of the crude used in the manufacture of motor

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[16] Thorne, H. M., and Murphy, Walter, A survey of the High-Sulphur Crude Oils (Black Oils) Produced in Wyoming: Tech. Paper 538, Bureau of Mines, 1932, 56 pp.

fuel, are deficient in light ends and have a sulphur content greater than 0.1 percent. These fractions will need blending with light material in order to meet distillation requirements and will require desulphurization treatment in order to meet the sulphur specifications for motor fuel.

These crudes can be made to yield more gasoline by cracking than is shown by the analyses in this report, but due to their high-sulphur and carbon-residue content, cracking offers difficulties of operation which make it necessary to design especially adapted equipment.

As this survey indicates, the black oils contain greater amounts of lubricating-oil stocks than many of the well-known lubricating-oil crudes, but the lubricating-oil stocks from these black oils will require extensive and expensive treatment due to their high-sulphur and asphaltic material content.

A series of tests on cracking typical black oils from the Oregon Basin, Garland, Grass Creek, and Dallas-Derby fields, and treatment of the products, is now being conducted at the Laramie (Wyo.) office. The tests are being made in a high-pressure experimental still having a capacity of 5 gallons, tested to 2,000 pounds per square inch, and operated at pressures up to 500 pounds per square inch. The object of the work is to determine the effect of cracking on the sulphur compounds and to determine how this cracking influences the distribution of sulphur in the various fractions.

It has been found that different pressures and temperatures have an effect on the decomposition of the sulphur compounds in the oil and on the yield of distillates, and some indications of optimum conditions of producing motor fuels from these crude oils by cracking are being obtained. The preliminary treating experiments on the distillate indicate the advantage of treating at low temperatures, but so far the amount of acid required is above the economic limit. Through the cooperation of a Rocky Mountain refiner, some detonation tests have been made on motor fuels obtained in the experimental work, which indicate that straight-run gasolines from black oils have a rather low octane rating.

Fractional Distillation of California Lubricating Crude Oils

In 1929, a study of the removal of asphalt and sulphur compounds from California lubricating crude oils by fractional distillation was started in the San Francisco laboratory.

This problem was undertaken at the completion of the engine service tests of internal-combustion engine lubricating oils made from California crude petroleum.[17]

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[17] The engine-service tests were initiated in 1923, in cooperation with the American Petroleum Institute, and reported by Gavin and Wade in 1926 in Bureau of Mines Technical Paper 387; followed by a companion study of the relationship between volatility and consumption of lubricating oils in internal-combustion engines, reported by Wade and Foster in Technical Paper 500 (published in 1931).

The growing use of vacuum distillation and efficient fractionation pointed to those refining methods as being superior to the prevailing refinery practices in California of partly removing these deleterious substances by chemical treatment and filtration.

To that end a laboratory batch still and a visible-action fractionating column, to be operated under vacuum, were designed and built to produce lubricating distillates under as nearly ideal conditions as possible in order that a subsequent study of the characteristics of the distillates could be made. The fractionating column is so arranged that it can be operated under adiabatic conditions, and localized or premature cracking of the oils in the still has been reduced to the minimum by a method of securing even heat transfer to the oil.

Three typical oils (Coalinga, Midway, and Kern) yielding California lubricating distillates were distilled at an absolute pressure of 1 mm. of mercury at the top of the column and 10.5 to 13 mm. in the still. A description of the still and column, the method of operation under vacuum, and tabular data on the physical and chemical characteristics of the close-cut fractions of the tests are given in Report of Investigations 3159.[18]

Since the initial report was issued, the batch still has been replaced by a pipe still in order that continuous operation can be maintained.

To evaluate the several products obtained in the still and fractionating tower, it was necessary to develop a method and apparatus to measure the stability of the lubricating distillates. Refiners on the Pacific coast have shown much interest in this method, developed by necessity out of the vacuum-distillation study, whereby it has been possible to assign numerical values to lubricating oils which will represent their ability to resist deterioration due to oxidation, polymerization, and condensation. The stability-test method is now being thoroughly reviewed and checked, both within and outside the Bureau, not only on western oils but on eastern oils as well.

Chemistry and Refinery Studies at Bartlesville, Okla.

At the Petroleum Experiment Station, Bartlesville, Okla., the major "sulphur-in-petroleum" problem has been under study, without interruption, since the petroleum laboratory was moved from Pittsburgh, Pa., in 1923. In fact, the sulphur problem has been of major importance to the petroleum industry since 1880-1885, and studies of many phases of the problem have been made by Bureau chemists and engineers.

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[18] Guthrie, Boyd, and Higgins, Ralph. Laboratory Batch Still and Fractionating Column for Production and Study of Lubricating Distillates under Vacuum: Rept. of Investigations 3159, Bureau of Mines, 1932, 18 pp.

A phase of the sulphur problem has been studied in recent years by the use of a visible-action continuous-distillation apparatus for laboratory study of fractionation. This device was described in Report of Investigations 2892, published in 1928, and was an exhibit at the International Petroleum Exposition at Tulsa, Okla., in 1929, where it attracted the favorable attention of many refinery technologists from this and foreign countries. The apparatus will form the nucleus of the Bureau's exhibit of petroleum refining by fractional-distillation methods at the "Century of Progress" in Chicago.

In a more recent study of the characteristics of Winkler County (Tex.) crude oil containing 1.49 percent sulphur, it was found that by proper fractionation and by dividing the gasoline into two or more fractions and treating them according to their several requirements, gasoline satisfactory as a motor fuel could be produced from this crude oil without as much chemical treatment and resultant losses as if it were produced from the crude oil in one stream. Complete results of three series of runs on this oil in the visible-action laboratory apparatus are given in Technical Paper 505.[19]

The Bureau has made a long-time study of various methods of refining light petroleum distillates. For some years its refinery engineers have maintained that proper fractionation of the gasoline yield of a pressure distillate will, with most distillates, decrease the amount of chemical treatment that will be required by the gasoline to meet trade requirements. The writers of Bulletin 333,[20] which describes various refining and treating methods, conclude that although "each crude and each pressure distillate has its own characteristics, and it is impossible to formulate a set of rules as to how much of each crude or each distillate should be taken overhead in the vapor phase and how much should be taken off the tower in the side stream," the beneficial results of the proper use of fractionation can not be denied. They recommend also that refiners investigate the possibilities of lessening the need of treating their products chemically by greater use of efficient fractionation and thereby reduce the attendant losses of valuable petroleum products.

Basing procedure upon the previously determined results of fractionating light petroleum distillates, and in line with other sulphur studies of the Bureau, work was started on high-sulphur paraffin-base lubricating oils at the Bartlesville station in the belief that the amount of sulphur compounds which cause bad color and odor in the oils can be reduced in the process of manufacture by means of proper fractionating equipment. To conduct this study, a bubble tower operating under vacuum has been designed and built. The tower, 6 inches inside diameter and 9 feet, 8 inches high, is so constructed that action within it may be observed through inspection ports. The tower assembly, together with a pipe still of the electric muffle-furnace type, condensers, receivers, vacuum pumps, a refrigeration unit, and necessary accessories, all of which are supported on a steel framework, is over 9 feet high, 8 feet long, and 3 feet wide. Preliminary runs have been made and a vacuum as low as 3 mm. absolute pressure can be maintained on the whole system. It is hoped that conditions will permit a series of runs to be started in the near future, in which various refining problems encountered in the manufacture of paraffin-base lubricating oils will be studied.

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[19] Espach, Ralph H., and Rue, H. P., Influence of Fractionation on Distribution of Sulphur in Gasoline: Tech. Paper 505, Bureau of Mines, 1931, 24 pp.

[20] Rue, H. P., and Espach, Ralph H., Refining of Light Petroleum Distillates: Bull. 333, Bureau of Mines, 1930, 111 pp.

Another phase of the sulphur problem has been a study at Bartlesville of methods for determining the sulphur in gasoline. In Technical Paper 513,[21] the authors, who studied a method of sulphur determination, concluded that "in general, the determinations of sulphur (made by them) proved quite clearly that the Edgar and Calingaert method, with the use of a sensitive indicator and provision against undue evaporation losses and improper lamp operation, is a very satisfactory method of obtaining check results and, in the case of some compounds, of accurately determining the percentages of sulphur in gasoline."

Wax-Distillate Problems

One of the administrative problems confronting the Bureau of Mines is to make available for use by the industry material that has taken years to collect. One such case before the Bureau is a study of methods of handling wax distillates in order to minimize the bad effects of amorphous wax. The problems involved in their wax content hinder large quantities of crude oil from becoming more valuable for the manufacture of high-grade lubricating oil. Work on a manuscript dealing with the manufacture and refining of wax was started by Wyant and Marsh in 1925. These authors prepared some excellent material before they resigned from the Bureau of Mines several years ago, but when an opportunity presented itself to publish the results, their work needed to be checked against recent developments in the art.

Prior to July 1, 1932, an engineer of the Bureau visited refineries to investigate present methods of handling wax, but his work has been delayed. Because the refinery group at Bartlesville is limited to three men, which does not permit conducting more than one active problem at a time, the definite decision has been made that pending work on fractionation of lubricating distillates in the large-scale vacuum-distillation unit, which has been mentioned, will not be carried forward until the revision of the paper on wax and wax distillates is completed. The industry will thereby be given the benefit of this investigation, extending over a period of years, and at the same time reducing the number of refinery problems under study - now too large for the force of technical men that can be assigned to them.

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[21] Espach, Ralph H., and Blade, O. C., Studies on Determination of Sulphur in Gasoline: Tech. Paper 513, Bureau of Mines, 1931, 22 pp.

Synthesis of Motor Fuels from Natural Gas

Not only has the art of manufacturing commercial products from petroleum experienced a revolution of ideas during the history of the Bureau of Mines, but ways of manufacturing products from natural gas, other than by the now conventional methods of natural-gasoline extraction, are no longer considered visionary.

Recognizing that large quantities of natural gas are being wasted because no ready market is available, a study was begun at the Bartlesville station in 1928 to develop possible methods of utilization through the synthesis of motor fuels from natural gas, using the principle of thermal-decomposition of natural gas, with temperature, pressure, and flow rate as the major variables. The aromatic hydrocarbons, especially benzol, are well-known antiknock motor fuels, and their economic manufacture from natural gas, especially from gas composed chiefly of methane, would provide a means of using much gas that is now wasted.

Various investigators had found points in common regarding the synthesis of light oils from methane, but they were not in agreement on many points, especially in relation to the temperatures necessary for maximum yield. Consequently, the Bureau, after a thorough review of the available literature, conducted work to devise apparatus and develop technique for the pyrolysis of methane. The preliminary report on this subject was given at Indianapolis before the American Chemical Society on April 3, 1931, and in October 1931, Report of Investigations 3143,[22] the first of a series of papers on the production of motor fuels from natural gas, was published by the Bureau.

Since the initial report was published, the laboratory experiments have been extended to include the processing of natural gas in a large-scale laboratory unit where calorized KA2 steel tubes, 6 feet long, with diameters of 1, 1½, and 2 inches have been used. Yields of 3/10 gallon per thousand cubic feet of gas have been obtained, and certain optimum conditions of operation have been established. In order to obtain a maximum conversion to light oils, a study also is being made of catalytic methods of hydrogenating the tars, which are produced in the pyrolitic treatment, by utilizing for this purpose the hydrogen present in the residue gas from the process. To complete this problem it would be necessary to build a test-plant unit for continuous and fairly large throughput.

Removal of Hydrogen Sulphide from Natural Gas

The hydrogen-sulphide problems of the petroleum and natural-gas industries have a three-phase relationship: namely, safety, corrosion, and removal by treatment. The first two phases will be discussed later in this paper. Methods of removal from natural gas more nearly fall within the group of chemistry and refining problems than do safety and corrosion, although actually one phase of the subject can not be adequately discussed without reference to the others.

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[22] Smith, H. M., Grandone, Peter, and Rall, H. T., The Production of Motor Fuels from Natural Gas - 1. Preliminary Report on the Pyrolysis of Methane: Rept. of Investigations 3143, Bureau of Mines, 1931, 12 pp.

A number of commercial processes have been developed for removing hydrogen sulphide from natural gas, but the problem is by no means solved in all its ramifications. The results of a special study made by the Bureau of Mines show that hydrogen sulphide can be removed economically from "wet" natural gas by means of a lime and salt solution, by contacting the gas and the solution in the proper scrubbing device. Both lime and salt are relatively cheap chemical reagents, and at one commercial plant where this method was tried, satisfactory economies in operation were effected.

In Report of Investigations 3178,[23] wherein this method is described, the further suggestion is made of the possibility of converting certain natural oil-field waters to the proper treating solution by the addition of relatively small amounts of certain chemicals, thus reducing the cost of the chemicals necessary to remove hydrogen sulphide from natural gas.

The Chemistry of Oils

Not all work on oils is directed to refining methods. Following the work of Allen and Jacobs,[24] the crude-oil surveys to determine the physical and chemical properties of petroleums and their relative values as sources of commercial products were extended, and today the Bureau of Mines collection of crude-oil samples is one of the largest. The Bureau's method of analysis,[25] developed as post-war work to meet the industry's requirements of that transitory and readjustment period, makes possible the comparison of different crude petroleums on a reproducible basis. The Bureau's classification,[26] in accordance with the "base" of an oil, is known and recognized wherever analyses of crude oils are considered.

More recently, because of the generally recognized need for information on the subject, much attention is being given to possible relationships between geologic depth and chemical characteristics of the oils. Such a study is being made of oils produced from sands of the eastern United States, and a manuscript discussing oils from the Eastern Hemisphere with reference to producing formations is now being reviewed by competent authorities in those fields. Many of the samples to be reported in the bulletin on crude oils of the Eastern Hemisphere were difficult to obtain, and only through the willingness of foreign countries and other agencies to cooperate with the United States Government were the samples delivered for analysis and subsequent report. The work of collecting samples of foreign crude oils has been in progress for more than 10 years. In connection with other studies, representative samples have been collected in the Oklahoma City field, and the analyses have been reported.[27] One report has been issued giving analyses of crude oils produced in East Texas,[28] and a subsequent report, in preparation, will discuss the characteristics of these and other East Texas oils in relation to their probable source beds.

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[23] Rue, H. P., The Use of Lime in a Salt Solution for Removing Hydrogen Sulphide from Natural Gas: Rept. of Investigations 3178, Bureau of Mines, 1932, 8 pp.

[24] Allen, I. C., and Jacobs, W. A., Physical and Chemical Properties of the Petroleums of the San Joaquin Valley, California: Bull. 19, Bureau of Mines, 1911, 60 pp.

[25] Dean, E. W., Hill, H. H., Smith, N. A. C., and Jacobs, W. A. The analytical distillation of petroleum and its products: Bull. 207, Bureau of Mines, 1922, 82 pp.

[26] Smith, N. A. C., The Interpretation of Crude Oil Analyses: Rept. of Investigations 2806, Bureau of Mines, 1927, 20 pp.

A major research related to the crude-oil surveys pertains to the chemistry of crude petroleum, as shown by the Bureau of Mines Hempel method of analysis. Although data are being accumulated on this subject through the analyses of representative oils, no opportunity has been given to prepare this material into a bulletin for publication.

This problem is typical of many that are under study by the Bureau of Mines. It was begun in the early years of research on petroleum, and like many others it is so fundamental that the general plan of attack has not radically changed. Many of these researches of the continuous type should be perpetuated in order to accumulate the knowledge that is required for the proper functioning of the industry.

Gasoline Surveys

Other studies pertain to marketed products. The surveys of motor gasolines by the Bureau of Mines date back to work in 1911 on comparisons of gasoline and alcohol as fuels for internal-combustion engines. It soon became evident that there was a dearth of published information on the quality of different motor fuels sold throughout the country. Following an initial report[29] on the physical and chemical properties of gasoline marketed in 1915, more extensive surveys were made in April 1917 and April 1919. Subsequently, the semiannual motor-gasoline survey of the Bureau was developed in response to an ever-growing demand for this type of technical information on the part of the manufacturers of motor fuels.

With the issuance of the twenty-first semi-annual motor-gasoline survey, it became evident that these surveys either must be discontinued or made more extensive in order to meet any objection that they were not showing a true cross section of the characteristics of marketed motor fuels. It was finally decided to extend the surveys, and the number of cities where samples were obtained was increased, and the number of samples collected was doubled to approximately 300. Also, samples of the gasolines tested in the routine laboratory of the Petroleum Experiment Station were sent to the Bureau of Standards, where through the cooperation of that Federal agency, detonation tests were made and the results reported, giving the first published survey of octane numbers of gasolines.[30]

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[27] Garton, E. L., Analyses of Crude Oils from the Oklahoma City Field, Okla.: Rept. of Investigations 3180, Bureau of Mines, 1932, 29 pp.

[28] Garton, E. L., Properties of Typical Crude Oils from the East Texas field: Rept. of Investigations 3130, Bureau of Mines, 1931, 7 pp.

[29] Rittman, W. F., Jacobs, W. A., and Dean, E. W., Physical and Chemical Properties of Gasoline Sold Throughout the United States During the Calendar Year 1915: Tech. Paper 163, Bureau of Mines, 1916, 44 pp.

The making of the gasoline surveys throughout the country entails a large amount of expense and work, particularly where a Bureau representative actually collects the gallon samples at service-station pumps in 20 cities, and increasing need of retrenchment forced the Bureau of Mines to discontinue the surveys with the issuance of reports on the survey of August, 1931.[31]

Since information on the properties of commercial motor fuels throughout the United States was desired by the industry, a canvass was made of representative oil companies who make gasoline surveys for their own information in their own marketing districts. It was thought that if these companies could supply the necessary information, the Bureau could analyze these results in much the same way as they had analyzed the results of their own analyses and continue to publish reports thereon, retaining, of course, the previous practice of keeping the identity of samples unrevealed. The response from the oil companies was indicative of their continuing interest. In fact, a dozen or more companies submitted data sheets, but these had to be returned to the senders, because in the first part of July 1932 it became evident that the Bureau would not be able to publish this information, for the reason that the Federal appropriation for oil and gas work had been greatly reduced. The only possible way by which these reports may be continued at the present time, and the intervening gap filled, is a definite action on the part of the industry through some of its agencies to arrange for the publication of these data which the Bureau is anxious to perpetuate in permanent record.

Routine Laboratory

As a very important adjunct not only to the refinery and chemical section but to the oil-field investigations and research problems as well, a routine laboratory has been maintained at the Petroleum Experiment Station, Bartlesville, Okla., since 1923, when the Bureau's work on the chemistry of oils was transferred from the Pittsburgh (Pa.) Experiment Station, in order that the technologic studies of all phases of petroleum by the Bureau of Mines would be more centralized. In this laboratory, analyses of samples of crude oils, distillates, motor fuels, oil-field waters, and natural gas are made.

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[30] Kraemer, A. J., and Lane, E. C., Twenty-second Semi-Annual Motor Gasoline Survey; Additional Data: Rept. of Investigations 3092, Bureau of Mines, 1931, 32 pp., including a section on detonation characteristics of motor fuels by the United States Bureau of Standards.

[31] Kraemer, A. J., and Lane, E. C., Motor-Gasoline Survey, August, 1931. Part 1 - Specification Data: Rept. of Investigations 3162, Bureau of Mines, 1932, 24 pp.
Kraemer, A. J., Lane, E. C., and Garton, E. L., Motor gasoline survey, August, 1931. Part II - Additional Data, with a section by N. R. White and H. K. Cummings on Detonation Characteristics of Motor Fuels: Rept. of Investigations 3175, Bureau of Mines, 1932, 31 pp.

Frequently, samples are submitted by individuals requesting an analysis of the material for commercial reasons. The Bureau's petroleum laboratory is not a commercial laboratory, although upon request it does a small amount of routine testing for other Federal agencies. The general practice is for the Bureau to collect or request collection of its own samples, and the senders of unrequested samples are referred to recognized commercial laboratories who are qualified to do the work in question.

Summary Statement

The foregoing review of the status of some of the Bureau's present studies, as they pertain to the chemistry and refining of petroleum and its products, is by no means complete. The reader should have gained, however, from text and footnote reference, a general idea of the types of problems under study and a suggestion of the results. Selected lists of Bureau of Mines publications pertaining to oil and gas are available to those who desire more complete reference to the published work on the several investigations.

(2) PRODUCTION OF GAS AND OIL

(Including related problems of pipe-line transportation of natural gas)

The same physical laws of flow, and certain fundamental relationships based upon these laws, hold for all fluids and fluid mixtures traveling in horizontal pipe lines, in vertical pipes, and in the intricate passages made up of the connecting spaces in porous media. Naturally, the character of the fluid and the walls of the conducting spaces change the form of the mathematical expressions describing the flow under a set of specified conditions. For this reason, engineers throughout the petroleum and natural-gas industries are endeavoring by many experimental methods to determine suitable numerical values for certain constants and exponents that may be applied in making computations. The objective is to obtain reasonable results without unnecessary refinements which may become meaningless in the light of other controlling factors.

From the foregoing statement, it is seen that studies of pipe-line transportation of natural gas have much in common with studies of flow relationships in the production of gas and oil.

The Annual Report of the Director of the Bureau of Mines for the fiscal year ended June 30, 1931, stated:

> The present problems pertaining to (1) flow of gas through pipe lines, (2) estimating reserves, (3) gaging and controlling natural-gas wells, (4) increasing the recovery of oil and related problems of flow of oil, gas, and oil-gas mixtures through porous media, (5) solubility of natural gas in crude oils, (6) vertical flow in wells, of which knowledge of flowing temperatures and pressures at various positions in the wells is so essentially a part, (7) injection of gas into partly depleted sands, and (8) migration of gas in reservoir sands are all essentially one large group of correlated research within the bureau.

For administrative purposes, these production problems are placed in four working sections - natural gas, oil recovery, vertical flow, and gas solubility - each section of which is connected actually, as well as diagramatically in the organization chart, to each of the other sections. As data are developed on any one of these problems, they strengthen the structure of the whole project of production research. For example, in the Bureau's study of pipe-line transportation of natural gas, flow relationships of the upstream and downstream pressures were found to have direct application not only to the study of vertical flow of oil-gas mixtures in wells but also to the study of oil-recovery problems which involve migration of oil and gas through sands and the spacing of wells.

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Natural Gas Problems

In the opinion of the Bureau of Mines, research problems of the natural gas industry and those of the petroleum industry are not subject to definite separation. This fact was clearly demonstrated in the cooperative report of the Bureau of Mines and the American Petroleum Institute entitled "Function of Natural Gas in the Production of Oil."[32] However, certain studies develop from conditions which are peculiar to the recovery and handling of each of these companion hydrocarbons.

The work on natural gas extends back to the Bureau's organization. For the past 10 years the problems have had a definite place in the industry's program through formal cooperation with the Natural Gas Department of the American Gas Association (formerly the Natural Gas Association). This work dates back to preliminary but very essential and basic tests by Cattell and Rawlins on the flow of gas through small orifices.[33] That work has now been extended to orifices of large diameter (up to 3½ inches) and a bulletin is in preparation which will cover all pressure conditions that would be found in the field or in experimental study.

On the basis of the small orifice relationships, a Nation-wide study of leakage losses from high-pressure natural-gas transmission lines was made, and a generally recognized method of determining these losses was developed which became a part of the code of the American Gas Association. Probably no gas-transmission line of any importance has been placed in operation since 1928, when Bulletin 265[34] was published, that was not thoroughly tested in accordance with the method described in that publication. In fact, on the 24-inch line from the Texas Panhandle to Chicago and on several others, engineers of the Bureau were called upon to give advice in order that the lines would be made safe and loss through leakage would be as small as possible.

Flow of Gas in Pipe Lines

Complementary to the gas-leakage work, another phase of the pipe-line studies was undertaken in 1925 in cooperation with the Natural-Gas Department of the American Gas Association - that of the flow of natural gas through pipe lines, which involves the economical handling and transportation of gas from the well to points of utilization. In their recent report to the pipe-line-flow committee of the association,[35] the Bureau engineers concluded that

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[32] Miller, H. C., Function of Natural Gas in the Production of Oil: A report by the U. S. Bureau of Mines and the American Petroleum Institute. Printed by the American Petroleum Institute, 250 Park Avenue, New York, N. Y., 1929, 267 pp.

[33] A brief résumé of this work was given before the Southwestern Short Meter Course at Norman, Okla., April 24-26, 1928. (Mimeographed under title: Rawlins, E. L., The Flow of Air and Natural Gas Through Small Orifices Under High Differential Pressure. 15 pp., 5 figs.)

[34] Rawlins, E. L., and Wosk, L. D., Leakage From High-Pressure Natural-Gas Transmission Lines: Bull. 265, Bureau of Mines, 1928, 108 pp.

[35] The data and findings are published in Rept. of Investigations 3153, Factor Influencing the Flow of Natural Gas Through High-Pressure Transmission Lines, by W. B. Berwald and T. W. Johnson, Bureau of Mines, 1931.

Weymouth's pipe-line-flow formula, when applied to pipe lines free from condensates and operating under steady flow conditions favorable to accurate measurements, will give a volume within a few percent of the measured delivery. From these findings, based upon tests on 29 commercial pipe lines and supplemental tests, it appears that a sufficiently accurate yet relatively simple criterion for the design, construction, and operation of natural-gas pipe lines has been established. The most pertinent conclusions made from this study are being incorporated into the code book of the Natural-Gas Department of the American Gas Association.

For greater accuracy, some investigators hold that the relationships between the coefficient of friction and the variables of the Reynolds' criterion should be applied in the design. However, for practical purposes in designing pipe lines for transmission of natural gas, the Bureau has found that -

> * * * the value of applying many small corrections to pipeline flow formulas, such as small differences in elevation between the inlet and outlet of the line, reduced diameter, fittings, the effect of bends, right-angle turns, metering stations, drips, type of joints, and the length of pipe between joints is often greatly diminished because of conditions affecting individual lines such as unsteady rates of flow, storage or drainage of gas taking place, the presence of condensates, rust, scale, and other foreign materials in the line, and the relative roughness of the interior walls of different lines. The effect of these conditions is often many times greater than the sum of all the measurable corrections.

A bulletin, augmenting Report of Investigations 3153, and giving the details of this study, is in preparation.

Deviation of Natural Gas from Boyle's Law and Viscosity of Natural Gas

Because of relationships involving the density and absolute viscosity of the gas, supplemental studies of these factors were necessary to correlate intelligently the data on the main problem of flow of gas through pipe lines. The results of these studies have been printed as Technical Paper 539,[36] and a companion paper by the same authors entitled "Viscosity of Natural Gas," Technical Paper 555, is in press.

The casual reader may wonder why engineers on practical research spend much time on what seemingly are problems of pure research and therefore should be dealt with in a highly specialized manner. The answer is that the essential facts which frequently are needed in the practical problem do not exist, so that in order to work out practical solutions, the engineer must make fundamental determinations that cannot be found in any handbook or other scientific writing.

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36 Johnson, T. W., and Berwald, W. B., Deviation of Natural Gas from Boyle's Law: Tech. Paper 539, U. S. Bureau of Mines, December 1932, 29 pp.

The principle of deviation of a gas from Boyle's law is fairly well understood and earlier writings have discussed the subject. However, Bureau engineers found that a procedure of experimental testing or actual measurement of the deviation under different conditions of pressure and temperature was essential, because (1) the deviation is a function of the chemical composition of the gas; (2) gases containing higher hydrocarbons deviate more than those having a larger content of methane; and (3) the chemical composition of a natural gas may change with a change in pressure or temperature due to liquefaction of some of the constituents. A large number of natural gases of different chemical composition were included in the study, making it possible to obtain a fair approximation of the compressibility of any natural gas by comparing its chemical composition with the gases reported in Technical Paper 539.

This work not only has direct application to natural-gas pipe-line-flow problems, but the deviation of natural gas from Boyle's law enters into the calculation of the actual volume of the void space in a sand body and the remaining pressures in the reservoir. It is recognized that the factors of water encroachment and possible errors in pressure and production records may introduce some uncertainties in calculation, but the deviation of natural gas from Boyle's law is likely to have a considerable effect on the estimates of future gas reserves, because when the deviation of the gas from Boyle's law is neglected, the amount of calculated reserve is higher than the actual amount of gas remaining in the structure. Since the publication of Technical Paper 529, the Bureau has had many inquiries from the industry regarding the application of the findings to special oil and gas field conditions.

Until recently, little consideration had been given to the subject of viscosity in solving natural-gas problems. Present-day industrial problems of the petroleum and natural-gas industries are dependent for their solution more and more on the application of the laws of fluid movement, and the report on viscosity, which is written in as nontechnical language as possible, should find wide practical use, equally as wide as has been found for the data developed in the study of deviation of natural gas from Boyle's law.

Methods for Gaging and Controlling Natural-Gas Wells

One of the most outstanding results of the cooperative work done by the Bureau of Mines and the Natural-Gas Department of the American Gas Association pertains to methods of gaging gas-well capacities. This method is commonly referred to as the "back-pressure method." Prior to the active cooperative work on this problem, tests were made in the Chickasha gas field in 1927 by Bureau engineers,[37] at the request of the Oklahoma Corporation Commission, which resulted in the establishment of certain relationships making it possible to evaluate the flow of gas from a well through a certain size of pipe to the equivalent flow through larger sizes, thus reducing the amount of gas blown to the air in an open-flow test. It was realized, however, that improvement in technique and greater savings in gas then wasted in the tests were possible.

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[37] Brandenthaler, R. R., Rawlins, E. L., and Johnson, T. W., Standardizing the Open Flow From Natural-Gas Wells: Rept. of Investigations 2885, Bureau of Mines, 1928, 6 pp. (out of print).

In 1929 two reports[38] were published outlining the fundamental relationships involved in the flow of gas through gas sands, and between gas flow and well capacities.

As explained in these reports, the basic thought of the fundamental relation between the three factors (1) rock or formation pressure in the sand, (2) back pressure at the sand face of the well, and (3) the rate of flow from the well, is that the sand of any particular gas well can be calibrated for its capacity to deliver gas from any formation pressure into any back pressure. In other words, there is a straight-line relationship between rate of flow and the difference of the squares of the formation and back pressures for delivery of gas from a formation pressure into a series of different back pressures when the data are plotted on logarithmic paper.

A total of 959 tests has been made on 577 gas wells in Louisiana, Ohio, Oklahoma, the Texas Panhandle, South Texas, and the Rocky Mountain area. In 88 percent of the tests it was possible, for all practical purposes, to draw the relationship as a straight line; in 8 percent, curvature was represented by the relationship; while in 4 percent of the tests, the relationship of the respective plotted points of the test series was irregular.

In some of the recent tests in Texas, it was determined conclusively by this method that cavings behind the casing were interfering with the flowing conditions of the wells. Other applications of the method point to the forecasting of drilling requirements, the design of gathering systems, determination of operating pressures, estimation of costs of production, and judging the advisability of storing gas in sands.

Discussion of many of the tests and their significance might be given, but only one typical example is cited to show how the use of the back-pressure method is saving gas in contrast to the open-flow gaging method where the gas is blown to the air.

In the Texas Panhandle area the equivalent open-flow capacity of 221 wells, which were tested by the back-pressure method, was determined to be approximately 5,485,000,000 cubic feet in 24 hours. It would have required an average of at least 30 minutes, and probably 1 hour or more to have obtained settled flow on these wells. Even with the minimum of a 30-minute flow period, an open-flow gage of these 221 wells would have wasted 114,000,000 cubic feet to the air. These figures do not include underground waste that would have been caused by the wide-open blowing of the wells. The hazards of water coning in the reservoir and detrimental effects on the mechanical condition of the wells because of open-flow tests are well known.

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[38] Pierce, H. R., and Rawlins, E. L., Study of a Fundamental Basis for Controlling and Gaging Natural-Gas Wells. Parts I and II: Rept. of Investigations 2929 and 2930, Bureau of Mines, 1929.

At first the method did not appear to many technicians as being feasible, but there has been a change in viewpoint, and since 1929, many of the tests on public lands, lands of the Osage Nation, and other Indian lands have been in conformance with this method. At an open meeting held some years ago in Oklahoma, it was agreed by the Corporation Commission that the back-pressure method might be used in all fields of the State as an alternate method until further notice. In Texas and Louisiana, the method has been looked upon with favor. In Montana no official action has been taken, but State conservation officers are showing interest. Recently the State of Michigan, desirous of having proper enactments which would help conserve its recently found gas resources, requested the assistance of the Bureau in order that when legislation was enacted the back-pressure method of testing well flows might be adequately provided for. Still more recently the State of Mississippi, faced with natural-gas conservation problems in the Jackson gas field, has called on the Bureau for assistance. Kansas also has asked for aid.

Judging from the foregoing results and the interest shown by the various States, the Bureau of Mines feels that the back-pressure method of determining the potential capacities of gas wells has proved its technical possibilities and its economic value.

Oil Recovery

Methods of production that leave large quantities of unrecovered oil underground are economically unsound and incompatible with true conservation. On this premise the oil-recovery section at the Bartlesville station was organized and its laboratory built and equipped in 1926, in order to determine, through experimental research, methods of increasing ultimate production in partly depleted fields and of prolonging the natural flowing life of wells. Since no research project requiring the development of a philosophy is ever undertaken by the Bureau of Mines until a careful canvass of its need has been made, several years of planning preceded the establishment of the oil-recovery laboratory as the nucleus of a definite project.

There are three active problems under study in the section:

(1) The flow of oil through sands.
(2) Methods of increasing the recovery of oil.
(3) The effect on crude petroleum of air used in repressuring oil fields.

Actually, problem 1 deals with fluid-flow through porous media and has a definite relationship to the work of the natural-gas section on methods of gaging and controlling natural-gas wells. This work also has special bearing on problem 2 dealing with increased-recovery methods of oil production.

Fluid-Flow Through Porous Media

The first series of experiments on problem 1 was conducted in order to obtain knowledge of the relationships of such factors as size and character of grain, permeability and porosity, and their effect on fluid flow. To this end, the natural-gas section and the oil-recovery section jointly performed a series of more than 60 experiments at the Bartlesville laboratory and at a special "hook-up" at a high-pressure gas well in the Texas Panhandle, made available for the experimental work by a gas company whose officials understood the objectives of and saw much promise in the results of the research.

In the initial tests, air and natural gas were flowed through various porous materials under different pressure and temperature conditions and at different rates of flow ranging from 0.2 to 700 cubic feet per minute and at pressures up to 435 pounds per square inch, absolute.[39]

In many respects the flow relationships involving the square of the upstream and downstream pressures were similar to those previously determined for the flow of gases through pipe lines. It was found, however, that there was a gradual transition from viscous to turbulent flow in contrast with the more or less abrupt change which takes place in straight pipes. It appears that the flow of gases through porous media conforms closely to the flow of gases in coiled tubes.

The results of the tests made it possible to determine an exponential equation that provided a helpful means of studying the effect on the flow conditions of such factors as grain diameter, shape of grain, and porosity. In addition, considerable progress was made in developing a method by which the relative capacities of sands to permit fluid flow through them could be compared accurately.

Different investigators had used different methods for expressing this sand quality, although each used the term "permeability." This led to some confusion regarding the meaning of permeability. The results of the Bureau investigation showed that a wide range of permeability factors might be obtained for a single sand, depending upon the rate of flow of the fluid through the sand. The reason for this is the change in flow conditions with changes in fluid velocities. It was evident that if the flow conditions in the various sands could be reduced to a common basis for comparison, the relative capacities of the sands to allow fluids to flow through them would have

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[39] The flow tubes were designed for a maximum working pressure of 1,500 pounds per square inch, with the view of making tests at this higher pressure on some special well. To date, the higher pressure work has not been performed.

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some significance. This basis of comparison was found in the determination of the "mean effective pore diameter" which could readily be made from the experimental data. A value for mean effective pore diameter is based upon the flow capacity of the sand under the conditions of viscous flow.

The determination of a mean effective pore diameter for each of the porous materials used in the tests shows a promising relationship between friction factor and Reynolds' Criterion through which the pipe-line flow formulas can be made more generally applicable to the flow of fluids through porous media.

A description of the equipment and a more complete discussion of the results of the tests are given in a paper by Chalmers, Taliaferro, and Rawlins in Transactions of the American Institute of Mining Engineers, Petroleum Development and Technology, 1932, under the title "Flow of Air and Gas Through Porous Media."

The findings and especially the interpretations of the permeability factor or "mean effective pore diameter" of a porous medium, in conjunction with back-pressure data, have application to well conditions in gaging the ability of a gas well to produce gas under different pressures, in calculating gas reserves, and in solving other practical gas-production problems.

All of the data thus far obtained have an important bearing on the problem of oil- and gas-well spacing. The problem of well spacing as a research project is not new,[40] but as yet it is generally agreed that no definite criteria have been established from which proper spacing patterns for various field conditions can be developed. This is an active problem before the industry, as indicated by studies that are being made by a special committee on well spacing of the American Petroleum Institute and by other organizations.

Engineers of the Bureau have been deeply interested in this problem and have regretted the fact that because of reduced appropriations, experimental work pertaining to the well-spacing program, as a part of the study of flow through porous media and other recovery problems, could not be extended this year to include work in a steel reservoir developed by Mills and his co-workers for studies of radial flow and described in Technical Publication No. 144 of the American Institute of Mining and Metallurgical Engineers, 1928.

However, the work on linear flow is continuing, and when the results on gas and air are satisfactorily analyzed, studies of the flow of oils through sands will be made before undertaking the more complex system involving oil with dissolved gas and oil-gas mixtures. To further the practical application of the work, cores of natural, consolidated sands are being checked against the unconsolidated sands of the previous experiments.

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[40] Beal, Carl H., and Lewis, J. O., Some Principles Governing the Production of Oil Wells: Bull. 194, Bureau of Mines, 1921, pp. 18-21, 25-34.
Brewster, F. M., A Discussion of the Factors Affecting Well Spacing: Trans. Am. Inst. Min. Eng., Petrol. Dev. and Tech. 1925, pp. 37-46.

Methods of Increasing the Recovery of Oil

At a time like the present when the possible rate of production from wells already drilled is in excess of what the market will absorb, the industry is especially interested in methods of curtailing production and bringing about orderly development. However, those who plan for the future realize that the fields now having "flush production" will have to be operated in a different manner in later periods of the life of the fields in order to recover the most oil and help pay out the development investments. The Bureau feels that sight should not be lost of the fact that even with the application of the best knowledge regarding natural flow in accordance with what is known of the function of gas in the production of oil,[41] nevertheless an appreciable quantity of the original oil will remain unrecovered in the sand except for the application of stimulative methods. The Bureau of Mines also has held that no matter how great the undiscovered reserves may be, they are subject to exhaustion, and a forward-looking view requires that knowledge be available when needed that will permit the winning of as much oil from the sands as may be possible. The laboratory investigations being made will give knowledge of the fundamental principles and relationships involved in various methods of increasing the recovery of oil from partly depleted fields.

Several publications[42] have described the equipment and methods used in the oil-recovery laboratory at Bartlesville. Recent work shows that when sand is highly saturated with oil, a wide variation in the rates of natural gas and air injection have only minor effect upon the efficiency of oil recovery by means of the "gas drive." However, for sands of low saturation the efficiency of operation, based upon energy-oil ratios, was greatly reduced with increased gas velocities.

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[41] Miller, H. C., Function of Natural Gas in the Production of Oil: A report by the Bureau of Mines and the American Petroleum Institute, printed by the American Petroleum Institute, 250 Park Ave., New York, 1929, 267 pp.

[42] Mills, R. Van A., Chalmers, Jos., and Desmond, J. S., Oil Recovery Investigations of the Petroleum Experiment Station of the United States Bureau of Mines: Tech. Pub. No. 144, Am. Inst. Min. and Met. Eng., 1928, 36 pp.
Mills, R. Van A., and Heithecker, R. E., Volumetric and A.P.I. Gravity Changes Due to the Solution of Gas in Crude Oil: Rept. of Investigations 2893, Bureau of Mines, 1928, 15 pp.
Chalmers, Joseph, Recent Studies on the Recovery of Oil From Sands: Trans. Am. Inst. Min. and Met. Eng., Petrol. Dev. and Tech. 1930, pp. 322-328.
Chalmers, Joseph, Nelson, I. H., and Taliaferro, D. B., The Recovery of Oil from Sands by the "Gas Drive": Rept. of Investigations 3035, Bureau of Mines, 1930, 12 pp.

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The earlier reported work of the Bureau on the "gas drive" showed that under the conditions of test, without back pressure, air had a greater propulsive effect than gas. Later comparative tests, where back pressures were held on the experimental flow tubes, showed that gas had a distinct advantage over air. Although the energy input was greater for gas than for air, the energy-oil ratio was less, because of the greater production of oil obtained by the use of gas.

It appears that in these flow-tube experiments the reduction of surface tension and decreased viscosity of the oil caused by the gas going into solution under back-pressure conditions tended to increase oil recovery, regardless of the fact that air was found to be more efficient than gas as a propulsive medium. As stated in Report of Investigations 3035 (see footnote 42), "The ideal gas for gas injection is therefore one that will dissolve freely in the oil at the injection pressure and will be liberated from solution by the time it reaches the producing well. Since there is seldom a choice of gas for injection purposes the same conditions may be approached by control of operating pressures."

Cognizant of the fact that laboratory results must have a direct "tie-in" with field operations, the Bureau has made studies of the flow of injected air and gas through oil strata. This work pertains equally to methods of increasing the recovery of oil by stimulative methods and to the recovery of oil by controlled natural flow.

Some time ago a study was made of the results of air repressuring in the Williams Pool, Texas, wherein it was shown that "high-pressuring" of the sands was detrimental because of by-passing and that increased recoveries could be obtained through the careful selection of input wells and the regulation of pressure. Results of this study are given in Technical Paper 470.[43]

More recently a study of the migration of injected gas through oil and gas sands of California has been made. Results of this field study showed that: (1) Injected gas migrates to regions where a lower pressure exists regardless of the structural location of such spaces with respect to the point of ingress of gas; (2) after the pressure within the intercommunicating pore spaces and low-pressure regions in the reservoir sands about injection wells have been equalized, the gas mass moves up the structure; and (3) bouyancy of injected gas alone is too small a force to move the gas mass or "bubble" any considerable distance up the structure, and the principle motivating force behind the up-structure migration of the "gas bubble" is the pressure of encroaching edge water.

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[43] Hill, H. B., Results of Air-Repressuring and Engineering Study of Williams Pool, Putnam-Moran District, Callahan County, Tex.: Tech. Paper 470, Bureau of Mines, 1930, 69 pp.

Gas injected into steeply dipping reservoir sands in California does not spread out fanwise from injection wells as many engineers and operators had previously supposed, and large bodies of oil-saturated sand between injection and producing wells are often by-passed by the injected gas. As in the case of the Williams Pool study, it was found that high injection rates with nonuniform spreading of injected gas make it difficult to control the direction of migration of the gas. The study proved further that the best results in increasing oil-recovery efficiencies are obtained by maintaining back-pressure on the producing wells to prevent gas from breaking through, and by limiting volume of gas injected through individual wells to a small amount per day so as to build up the reservoir pressure gradually. Report of the detailed findings are given in Report of Investigations 3177.[44]

Effect of Crude Petroleum of Air used in Repressuring Oil Fields

Several years ago when the use of methods of stimulating oil production were at a rather high peak, many questions were asked as to whether or not air in repressuring work would change the chemical composition and physical characteristics of crude oil. Other questions of a similar nature were: Are all types of crude oils oxidized by the use of air? Will the use of air seriously affect the viscosity and surface tension of the crude oil so that it will be more difficult to remove from the sand? Will the use of air change the character of the oil sufficiently to decrease its commercial value? Can the oxidation of crude oil be prevented by the use of inhibitors?

Relatively long-time experiments with oils of different chemical characteristics have been in progress in a specially constructed temperature bath at the Bartlesville (Okla.) station in an effort to answer some of these questions. Some of the tests have been run for a period of 182 days. In order to determine the plugging effect that might result from the formation of precipitated gums, resins, and asphaltic material, the oxidized oils were flowed through tubes packed with definite quantities of finely screened Wilcox sand of a known porosity. In flowing the oxidized oils through the tube a decided plugging of the sand takes place, and the flow of oil is stopped or greatly retarded after only a small quantity of oil has passed through the tube. In this way it has been determined that a satisfactory recovery of oil would be almost impossible if oils in the sand reached a state of oxidation of the same degree as that obtained in the experiments.

The emulsification of oils has been studied also in connection with the use of air as a repressuring medium. While many of these tests in the laboratory have been accelerated by the use of oxygen, the report of the work will treat the subject in such a way that the results may be made to approach

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44 Miller, H. C., Migration of Injected Gas Through Oil and Gas Sands of California; Rept. of Investigations 3177, Bureau of Mines, 1932, 29 pp.

average field conditions as nearly as possible. With the issuance of a report on the effect on crude petroleum of air used in repressuring oil fields, the Bureau feels that, for the present at least, it will have satisfactorily answered the most urgent questions regarding changes in the chemical and physical characteristics of crude oil where air is used as a repressuring medium.

Vertical Flow (Including a Study of Pressures and Temperatures in Wells)

The flow of oil, gas, water, or a combination of these fluids takes place because of the differential pressures existing within the system. In solving problems of fluid flow, the petroleum engineer is concerned with two systems, each dependent and exerting a positive effect on the operation of the other. One system includes the space within the reservoir; the other is the vertical column from the face of the sand to the surface of the well.

With this thought in mind, engineers have been working on methods of determining pressures and temperatures in the reservoir for a number of years in order to correlate the fundamental laws of thermodynamics, mechanics and physics, and data obtained in laboratory studies with actual problems encountered in the production of oil from the reservoir and in lifting it to the surface.

In 1928, K. B. Nowels, then supervising engineer of the Bureau's Laramie (Wyo.) field office, recognizing the need for determining the pressures that exist at the bottoms of the wells, began the development of an instrument that would obtain these data which were needed in a study of the energy requirements of vertical flow in wells. It was believed that data on this subject would aid operators in selecting proper sizes of tubing and would make possible the efficient flowing of oil wells with their natural energy and delay the time of exhaustion of the natural energy in the reservoir required to lift the oil to the surface. A second phase of the problem pertains to determinations of the energy requirements for the most efficient flow of oil, gas, and water, or mixtures of these fluids through reservoir sands. Work was inadvertently delayed on this problem through the resignation of Nowels from the Bureau to engage in other work, but during the spring and summer of 1932, a pressure and temperature bomb was developed by C. E. Reistle, Jr., at the Bartlesville (Okla.) station, suitable for the work of the Bureau in studying the thermodynamic and other relationships of vertical flow.

After calibrating the bomb with other instruments developed during the interim period, that had proved satisfactory, a definite study was begun in the East Texas field at the request of operating companies. This work was carried on simultaneously and in conjunction with similarly requested studies of the solubility of gas in the oil under reservoir conditions, to which reference will be made in the following section of this paper.

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The Bureau's work on pressures and temperatures in wells in east Texas is different from the periodic "bottom-hole pressure" surveys which have been made by the companies and by the State conservation officers. These organizations have equipment and personnel for making the necessary surveys of pressure conditions which recently have been recognized as an important factor if rational production-control programs are to be established.

The tests of the Bureau include pressure and temperature measurements at various points in the flow strings and at the well heads of selected wells under different rates of flow, both with and without the use of bottom-hole chokes. From these data it is believed that fairly accurate predictions can be made of minimum bottom-hole pressures that will be required to maintain natural flow. These data also should help in solving the problems that will be encountered in the operation of flowing wells in the East Texas field due to the accumulations of paraffin on the face of the sand and the flow columns. A report on "A Study of Subsurface Pressures and Temperatures in Flowing Wells in the East Texas Field and the Application of these Data to Reservoir and Vertical-Flow Problems" was given by Reistle and Hayes before the American Petroleum Institute, Tulsa, Okla., in May 1933, and published in Report of Investigations 3211.

Solubility of Gas in Oil

The industry has long recognized the very important phenomena of the solubility and effects of natural gas and air in crude oils, but it has been the objective of investigators to know whether or not the same straight-line relationships between volume of gas and pressure at which the gas comes out of solution in accordance with Henry's law hold true under reservoir conditions, as has been found in experimental work, where relatively dry gases have been put into solution through the exertion of pressure upon relatively stable samples of crude oil.

To this end, samples were obtained in the Oklahoma City, Kettleman Hills, and Ventura, Calif., oil fields at the casingheads of wells in the pressure range of 1,100 to 1,700 pounds per square inch; after the Bureau had determined by personal discussion or correspondence with representative engineers in all parts of the country that a large majority of these men believed the problem to be one of the most important research projects confronting the petroleum and natural-gas industries.

This inquiry and subsequent developments indicate that there is a growing opinion among engineers and others that the solution of technical and economic problems of the petroleum and natural-gas industries requires the application of fundamental laws and relationships. It is now generally recognized that none of the relationships of fluid flow in reservoirs and in the vertical columns of wells can be thoroughly understood and applied practically without knowledge of pressure and temperature conditions in the wells and the amount and character of naturally dissolved gas in the crude oil and of the conditions which control the liberation of this gas from solution.

From the initial work on casing-head samples of oil-gas mixtures, it was determined that the manner of gas liberation has a definite effect upon the shape of the solubility curves which represent the amounts of gas in solution in the oil at various pressures. Two general types of liberation were recognized - differential liberation and so-called "flash liberation." When gas is liberated from solution differentially, the gases are removed from contact with the oil as rapidly as they are liberated from solution. The essential requirement for "flash liberation" is the presence at the lower pressure (as at the well head) of all the components of gas and oil that are present at the higher pressures (as at the well bottom). The experiments showed that in differential liberation, greater quantities of gas are released from solution per pound pressure drop at low pressures than at high pressures. Such conditions produce solubility curves that are curved, rather than the straight lines in accordance with Henry's law, that were obtained by the earlier investigators who performed their experiments with comparatively dead oil and dry natural gas. In "flash liberation" the gas comes out of solution quite differently from differential liberation, and the solubility graphs resulting from "flash liberation," under conditions where a considerable amount of free or excess gas is present, apparently approach the straight-line relationship in accordance with Henry's law, even though the gas in solution contains appreciable quantities of heavier gases and might be classified as "wet" gas.

The investigators of the problem think that it is probable that differential liberation of gas occurs with respect to the major portion of the oil in a natural underground reservoir, whereas "flash liberation" occurs in the flow string of a well.

These studies of gas liberation also have a direct bearing upon the knowledge of volumetric changes of the oil in the reservoir. It was found that the heavier gases which are liberated at pressures below 100 pounds per square inch absolute, cause much greater shrinkage in the oil and much less reduction of pressure than equal volumes of the lighter gases.

After the data obtained from well-head samples were thoroughly analyzed and conclusions drawn,[45] a "bottom-hole thief," or sampler was constructed for the purpose of obtaining samples at the bottom or at any point in the flow string of the well. The instrument was first given a practical test in the Seminole (Okla.) field, where bottom-hole samples at 400 pounds per square inch pressure were obtained, and more recently has been giving satisfactory service in the East Texas field where reservoir pressures range from 1,400 to 1,500 pounds per square inch.

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[45] Lindsly, Ben E. Solubility and Liberation of Gas from Natural Oil-Gas Solutions: Tech. Paper 554, Bureau of Mines (in press). (Preliminary report given in Trans. Am. Inst. Min. and Met. Eng., Petrol. Dev. and Tech. 1931, pp. 252-278.)

The present program of field work in east Texas, made possible by the cooperation and financial aid of several oil companies, has been completed. Satisfactory solubility curves for both differential and flash liberation have been obtained at 146°F. and at 90°F. According to the analysis of the data, naturally dissolved gas in the East Texas oil does not begin to come out of solution and expand until the pressure is reduced to 755 pounds per square inch, absolute. Above 755 pounds per square inch absolute, liquid expansion takes place upon a reduction in pressure. Compressibility and shrinkage curves for the oil at the indicated temperatures also have been plotted from the well data.

The more detailed results of this study have been given in a paper by Lindsly entitled "A Study of 'Bottom-hole' Samples of East Texas Crude Oil," before the American Petroleum Institute, in May, 1933, at Tulsa, Okla., and published in Report of Investigations 3212.

Field work in east Texas, on the two related problems of vertical flow -- including pressures and temperatures in oil and gas wells -- and solubility of natural gas in crude oils, had to be suspended for lack of funds after June 30, 1932. Learning that the engineers working on these two problems were to be called back to their headquarters because there was no appropriation to permit them to stay in the field and complete their study (even though the Bureau realized that the results were especially needed at that time in solving problems of rational production-control in the East Texas area) several of the operating companies, who had closely followed the work, took the initiative and devised a plan. Through the generous financial cooperation of 14 or more producing companies, the Bureau engineers were enabled to remain in the East Texas field and finish the tests.

This cooperation of the oil companies, not only in supplying funds to finish these tests, but in making wells available for study, is an outstanding example of cooperative efforts by the Bureau of Mines and oil companies to solve the industry's problems of rational and economical oil production.

Recently, the Bureau began somewhat similar types of solubility and vertical-flow studies in wells of the Oklahoma City field. As conditions will permit, it is hoped that other fields may be studied, thereby making the experimental data more generally applicable throughout the industry and at the same time obtaining specific information on various individual fields that will assist the producers in those fields to operate their wells at maximum efficiency under the conditions imposed by the economic state of the industry.

Summary Statement

This review of some of the major problems pertaining to the production of oil and gas, and related natural-gas transportation problems, in which the Bureau of Mines is actively engaged, indicates the significance of coordinating research in arriving at applied production-engineering methods.

Through these coordinated studies in the laboratory and in the field the fundamental relationships of fluid movement have been found beyond a reasonable doubt to be common to the solution of such problems as the transportation of natural gas through pipe lines, gaging and controlling of natural-gas wells, flow of oil and gas mixtures from the sand face of the wells to the surface, recovery of oil by natural-flow methods wherein proper patterns of well spacing and control of pressures in the reservoir and in the flowing columns are important factors, and recovery of additional oil by imposed stimulative methods of production after reservoirs have been partly depleted. In all of these named practical problems, and others which are met in the production of oil and gas and in their transportation, knowledge is necessary concerning the relationships of the hydrocarbon constituents as affected by pressures and temperatures. In other words, knowledge of the amount of gas naturally dissolved in oil under reservoir conditions and the liberation of this gas from solution upon dimunition of pressure, not only at the surface but in the flowing column and in the reservoir as well, is basicly important in reaching reasonable conclusions regarding this group of correlated production problems, some general results of which have been given.

(3) ENGINEERING FIELD STUDIES

In addition to practical research on problems of oil and gas, the Bureau of Mines conducts engineering studies of typical and important oil and gas fields. These studies are concerned with conditions that influence or control the production of oil and gas. Primarily, they are based upon the correlations of the subsurface formations that constitute the reservoirs and that naturally influence the withdrawal of oil and gas from them.

Detailed studies are made of the logs of the wells in order to find out important information such as suitable landing depths for casing; well penetration into producing zones; the character of the sands and of the oil; water conditions throughout the field; the position of so-called "thief sands;" and many others which may aid economic recovery or hinder operators from obtaining maximum recovery with minimum expense. In addition, the history of a field under study is kept as accurately as well-completion and production records will permit, and methods and equipment at the surface are studied in their relation to subsurface conditions.

These engineering reports on typical fields may be dated from a report issued in September 1919 on the Comanche (Okla.) oil and gas field,[46] although some reports on the Rocky Mountain area were made prior to that time.[47] Since then some 35 reports have been published on fields in Oklahoma, Texas, Louisiana, Arkansas, and the Rocky Mountain region.

Although several field studies are in progress, the Bureau's major activities in this work are now centered in the Oklahoma City pool. This work was started actively in June 1930 after the Bureau made a careful review of the situation to determine the need for such a study.

A report on "The Use of Boiler Feed-Water Heaters with Steam-Powered Rotary Drilling Equipment," by C. E. Reistle, Jr., was published in July 1930 as Report of Investigations 3022, and a paper giving analyses of oils produced in the Oklahoma City field has been issued.[48] A technical paper describing mechanical processes and equipment which were brought out by the industry during the development of the high-pressure sands of the Oklahoma City field is in course of publication.

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[46] Swigart, T. E., Underground Problems in the Comanche Oil and Gas Field, Stephens County, Okla.: Bureau of Mines engineering report in cooperation with the State of Oklahoma, Sept. 1919, 42 pp.

[47] Tough, F. B., and others, Report of Operations From May 16, 1919 to May 15, 1921: Rocky Mountain Petroleum Association, in cooperation with the U. S. Bureau of Mines, 93 pp. (out of print).

[48] Garton, E. L., Analyses of Crude Oils from the Oklahoma City Field, Oklahoma: Rept. of Investigations 3180, Bureau of Mines, 1932, 29 pp.

The issuance of the detailed report on the Oklahoma City field, as it pertains to underground conditions and oil production, has been postponed because of the definite request of the Oklahoma City Chamber of Commerce to prefer a supplemental study of the possible gas reserves in the Oklahoma City field. The gas-reserve report seemed to be more urgently needed than the detailed oil report, and accordingly petroleum and natural-gas engineers of the Dallas office and Bartlesville station, since May 1932 have been concentrating their efforts on this engineering study, which has many economic factors.

A summary report was submitted to the Chamber of Commerce in February 1933, and the detailed "Estimate of the Gas Reserves of the Oklahoma City Oil Fields," comprising 100 manuscript pages, 13 tables, and 15 maps and cross sections, will be available for general distribution and study as soon as it can be printed.

Peg models showing the underground conditions of fields have been a working tool of the Bureau engineers for many years. In the study of the Oklahoma City field, a new type of model showing reservoir conditions from the top of the Oswego limestone to the oil-water contact, has been built. This model is not only unique in design but has been beneficial in giving a visual picture in three dimensions of the contacts of the various formations, the water conditions in the field, and other underground conditions. It is called the "egg crate" model. Sections through the field have been made along east-west and north-south lines of wells. The correlations have been worked out, and the sections showing the logs of the wells have been pasted on one or both sides of stiff cardboard slotted at the proper intervals. When these various sections are fitted together in a manner similar to the construction of an egg crate, a graphic picture of the oil-producing formations is given. Any of the east-west sections can be removed for detailed study without disturbing the rest of the model. The model of the whole field is approximately 14 feet long and 9 feet wide, and has a vertical scale of 100 feet to the inch.

This model has proved to be very helpful in visualizing and understanding the underground conditions of the field.

Prior to the special work on gas reserves of the Oklahoma City field, a preliminary draft of a manuscript dealing with reservoir and subsurface conditions of the Oklahoma City field had been written. Since many of the data were confidential at the time they were furnished by the companies, their release from the companies must be obtained, and other data must be added to bring the report up to date, before the writing can be prepared in final form for publication. Upon several occasions, Bureau of Mines engineers, upon invitation, have attended meetings of engineering committees and have discussed informally with State officials and company engineers technical problems which are of vital concern in the Oklahoma City field.

Among the recently completed field studies is a report on crater wells in the Richland gas field, La.[49] At the instance of the Department of Conservation, State of Louisiana, engineers of the Bureau studied the histories of these seething pits of mud and water through which vast quantities of natural gas were lost for all time. One of the crater wells burned for many months. The report gives data on the cause and repair of crater wells and suggests methods of repair and the importance of preventive measures.

At the completion of a study of the Cotton Valley field,[50] often referred to as an example of a typical ideal textbook structure, a study was begun of the structural features and conditions controlling the accumulation of oil in the chalk and limestone reservoirs of the Zwolle (La.) field.

The Zwolle area is unique in many respects. The limits of the field have not been defined, but the area under development to date is a strip approximately 22 miles long, with an estimated average width of 2 miles. The field now has a maximum width of about 4 miles. The percentage of dry holes is exceedingly high (approximately 60 percent), and many of the commercial wells have been drilled as offsets in the vicinity of the dry holes. In the Zwolle area, acid has been introduced in many wells in an effort to increase the production of oil from the chalk or limestone formations. As in fields of Michigan, this "acid treatment" is reported as being beneficial in stimulating the flow of oil from the producing formations to some of the wells.

With the opening of fields in the great Permian Basin of the West Texas area, attention was drawn particularly to the Roberts-Settles field in Howard and Glasscock Counties. In December 1928, at the request of the Railroad Commission of Texas and the operators, the Bureau gave engineering advice and assistance in a subsurface study of that field, typical of the "lime production" of west Texas. When the work was initiated, it was proposed to prepare a brief report, within a short period, on the water conditions in the 3,000-foot producing zone. Bureau engineers worked with the operators' engineering committee in studying the water problem and in formulating plans to control premature edge water encroachment. A short report, summarizing the results of the investigation and recommending some remedial measures, was submitted to the Railroad Commission in March 1929.

Since the work was begun, other issues affecting the development of this field have arisen. The productive area was extended; new producing horizons have been found; and the entire field has been put under proration. Throughout this transitional period, the collection of additional data on this and other west Texas fields has continued.

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[49] Hill, H. B., Crater Wells, Richland Gas Field, La., Tech. Paper 535, Bureau of Mines, 1932, 37 pp. 28 figs.

[50] Ross, J. S., Engineering Report of the Cotton Valley Field, Webster Parish, La.: Tech. Paper 504, Bureau of Mines, 1931, 69 pp.

In its effort to complete as many pending problems as possible, the Bureau has assigned one of its engineers to the specific duty of preparing a report for publication which will discuss the Roberts-Settles district as a type field and present outstanding data on the other Permian Basin fields. In the report emphasis is being laid on reservoir conditions, water history, development methods, operating practices, and recovery values, and their economic aspects as applied to limestone reservoirs.

The engineering field reports of the Bureau of Mines not only have a present value, but in the long-time view, they serve as indisputable records, helping in the necessary later repair of wells and in the recovery of oil left in the sand during earlier stages of production. The Bureau's report on the Powell (Tex.) field may be cited as typical of the lasting benefits derived from such studies. Actual work of collecting data and records in this field began in January 1924. Throughout the active producing life of the field, Bureau engineers have been in touch with field operations and have followed in detail the application of remedial measures and the results of the generally adopted "plugging back" program in the field, recommended by the Bureau to control water encroachment and to avert the early menace of flooded wells. In recent months, the published report of the Powell field[51] has been in as great demand as at the time it was issued.

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[51] Hill, H. B., and Sutton, Chase E., Production and Development Problems in the Powell oil field, Navarro County, Tex.: Bull. 284, Bureau of Mines, 1928, 123 pp.

(4) SPECIAL ENGINEERING PROBLEMS

There is another class of problems, involving certain phases of all the engineering sciences, referred to in the earlier reports of activities of the Bureau of Mines under the heading "engineering technology." Within the petroleum and natural-gas division they are now known as "special engineering problems," although each problem has its own research philosophy. They are undertaken, studied, suspended, or made continuous in the same manner as the refinery, chemistry, and production studies are treated - namely, on the basis of whether or not they justify the effort and money to be expended upon them. This group includes studies of methods of shutting in oil wells, evaporation losses, tank corrosion and internal corrosion of pipe lines, disposal of oil-field brines, hard facing metals for oil-well tools; safety in the petroleum industry, and the compilation of a petroleum bibliography.

Methods of Shutting in Oil Wells

Present economic conditions may be partly responsible for the Bureau's undertaking what was planned as a "short-time" study but which may prove to be the subject for a much longer investigation than was contemplated. This problem deals with methods of temporarily shutting in pumping and flowing wells.

The detrimental effects of water and the losses of oil and gas trapped in sands due to the flooding of productive horizons is now well understood in the industry, and the protection of their correlative rights in a pool has led operators to complete their wells so that losses from this source have been reduced to a very small portion of what they were in former years.

However, production control leading to the need for temporarily shutting in wells after they have been on production for some time, has introduced new factors into this problem, and the shutting-in of wells becomes more than a matter of closing a valve at the casing head or stopping the pump. It is imperative that oil sands exposed in shut-in wells be protected from infiltrations of water from upper and lower water sands, and that the "thief" sands should be sealed to prevent the loss of oil and gas. Very little information is available concerning methods of preparing wells, especially those which have penetrated a series of oil and water sands under different pressures and which have different characteristics, so that these wells may be shut in for a period of time without underground losses.

The Bureau is making an active study of this subject. Filling wells with mud fluid, oil, cement, or a combination of two or more of these materials has been tried, and the experiments are being carefully watched. Experiments are also being made to devise ways whereby these sealing materials may be removed from the wells at a later date without injury to the producing characteristics of the wells.

Prevention of Evaporation Losses

Studies of evaporation losses of petroleum and gasoline were begun in the early years of the petroleum division of the Bureau of Mines. The first work pertained to crude-oil studies, and in sequence losses due to evaporation of gasoline at refineries were studied and reports issued thereon. The more recent studies pertain to methods of reducing evaporation losses at gasoline bulk-storage plants. No complete through-put test at a bulk-storage plant has yet been made, but Report of Investigations 3138,[52] giving the results of tests on standing storage, has helped show the relative magnitude of losses that may be expected from different types of tanks in use at the distributing centers.

Tests have just been completed on two vertical gasoline storage tanks, approximately 11 feet in diameter and 18 feet high, with a capacity of about 12,500 gallons each. These tests were made at Bartlesville, Okla., and will supplement data obtained in previous tests at Kansas City, Mo., reported in Report of Investigations 3138.

The study of evaporation losses appears to be a continuous problem regardless of the fact that through the initial studies of this subject by the Bureau, the industry was made aware of the enormous losses that could be controlled and reduced by the use of properly constructed tank equipment and auxiliary devices. For several years results of the Bureau's studies of evaporation losses have been published only as mimeographed reports, and the Bureau finds itself in a position of no longer having available for distribution many of the reports on evaporation which have been issued. To correct this condition, a bulletin is in preparation which will incorporate the essential findings given in the mimeographed reports and to which will be added many data not contained in them.

Studies of Internal Corrosion

The study of tank corrosion is another engineering problem on which several reports[53] have been issued. Particular interest in this subject developed at the time that fields producing high-sulphur petroleums and hydrogen-sulphide-bearing gases became a factor in the production of crude oil in the United States.

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[52] Schmidt, Ludwig, and Wilhelm, C. J., Reduction of Evaporation Losses from Gasoline Bulk Storage Tanks: Rept. of Investigations 3138, Bureau of Mines, 1931, 11 pp.

[53] Schmidt, Ludwig, Devine, J. M., and Wilhelm, C. J., The Use of Aluminum for Oil Lease Tanks: Part I - Field Tests; Part II - Laboratory Tests: Rept. of Investigations 3066 and 3131, Bureau of Mines, 1931, 17 and 16 pp., respectively.

Devine, J. M., and Wilhelm, C. J., The Effect of Oxygen on Gaseous Hydrogen Sulphide Corrosion of Tank Steel: Rept. of Investigations 3160, Bureau of Mines, 1932, 19 pp.

From knowledge gained through studies of gaseous corrosion as applied to tanks, it was a logical move to apply these findings to conditions which cause internal corrosion of natural-gas transmission lines. Laboratory tests have been made on various test specimens of materials used in tank and pipe-line construction, and tests have been made in the field to determine what concentrations of hydrogen sulphide and moisture produce the deleterious effects.

In one pipe line, concerning which Bureau engineers were called upon to give the benefit of their experience pertaining to internal corrosion, it appeared at first that the corrosion was occurring at variance with previously established conclusions. Subsequent investigations, however, revealed that the corrosion was not ordinary gaseous corrosion but was a modified form that has been termed "modified gaseous corrosion."

"Modified gaseous corrosion" differs from ordinary gaseous corrosion mainly in that the gas is not only saturated with water vapor but the surface of the subjected metal is also covered by a visible amount of liquid water.[54]

After making some changes in the previous laboratory procedure, it was determined that (1) "modified gaseous corrosion" proceeds as a straight-line function of the pressure that exists on the gas; (2) "modified gaseous corrosion" is a more severe form than ordinary gaseous corrosion, and less hydrogen sulphide is required to promote a severe action; (3) "modified gaseous corrosion" can proceed where there is almost no hydrogen sulphide present because of oxygen, but such corrosion is not great; (4) "modified gaseous corrosion" is more nearly the type of corrosion that occurs under field conditions than the gaseous corrosion previously studied.

As a part of its work on hydrogen sulphide, the Bureau made a survey of producing areas in Illinois, New Mexico, and Texas, and a report[55] was issued on the hydrogen sulphide content of gas in 165 wells, representing 15 oil fields in those States. The percentage of hydrogen sulphide in natural gas produced in various fields ranges from a fraction of 1 percent to as high as 20.5 percent by volume. The extent of fields where hydrogen sulphide is produced with gas and the concentrations encountered clearly indicate that the problems growing out of hydrogen sulphide are of continuing major importance to the petroleum and natural-gas industries.

Disposal of Oil-Field Brines

In many fields as production declines, and particularly where the production is due to an advancing front of salt water, the disposal of brine becomes a serious economic problem to the operators, the owners of property where land

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[54] Devine, John M., Wilhelm, C. J., and Schmidt, Ludwig., Corrosion of Gases Containing Traces of Hydrogen Sulphide: Tech. Paper 560, Bureau of Mines (in preparation).

[55] Devine, J. M., and Wilhelm, C. J., Hydrogen Sulphide Content of the Gas in some Producing Fields: Rept. of Investigations 3128, Bureau of Mines, 1931, 15 pp.

and stream pollution become acute, and to the States. Many oil operators have recognized their responsibility to take care of these wastes, and large nonprofit organizations have been formed in a number of fields in order satisfactorily to take care of an inevitable condition. Producing and refining companies have spent large sums of money to prevent the nuisances, which are in fact economic losses, caused by oil-field brines and refinery wastes.

Some years ago, joining in a Nation-wide study of the problem, the Bureau prepared several reports[56] in reference to contamination of navigable waters and performed an acknowledged service in helping to create a national consciousness regarding this form of preventable waste. More recently particular attention has been given to oil-field brines. At the request of operators and the State of Oklahoma, for example, a study was made of oil-field water-disposal methods. These findings were printed in Report of Investigations 2945.[57] Following this report, disposal methods as practiced in the Salt Flat field of Texas were discussed in Report of Investigations 3059.[58] In this field the highly saline waters are impounded and released to the streams for dilution to unharmful concentrations at periods of high flood. Another report[59] deals with disposal of oil-field brines in the Hendricks oil field.

Many proposals and several attempts have been made to return oil-field brines to underground reservoirs -- presumably in barren formations or down dip from the oil-water contact. Theoretically this practice is logical, but Bureau engineers found that practical considerations should be studied carefully in each area. Some salts will soon clog the pores at the face of the sand of intake wells. Prohibitive pump pressures may develop, and the possibility of contaminating underground sources of potable water or the injury of possible oil and gas producing horizons should be studied carefully and expertly

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[56] Lane, F. W., Bowie, C. P., and Desmond, J. S., Pollution by Oil of the Coast Waters of the United States. Rept. of Investigations 2658, Bureau of Mines, 1924 (out of print).

Report to the Secretary of State by the Interdepartmental Committee, Oil Pollution of Navigable Waters (March 13, 1926, 119 pp.) Appendix 3, General Report of the Bureau of Mines on pollution by oil of the Coast waters of the United States, Jan. 6, 1926, pp. 35-69. Appendix 4, Report of the Bureau of Mines on the action of sea water on fuel oil, Oct. 1925, pp. 70-75.

Lane, F. W., and others, Typical Methods and Devices for Handling Oil-Contaminated Water from Ships and Industrial Plants. Tech. Paper 385, Bureau of Mines, 1926, 64 pp.

[57] Schmidt, Ludwig, and Devine, John M., The Disposal of Oil-Field Brines; Rept. of Investigations 2945, Bureau of Mines, 1929, 15 pp.

[58] Hill, H. B., Bauserman, E. V. H., and Carpenter, C. B., Development and Production History of the Salt Flat and other Fault Fields of East Texas: Rept. of Investigations 3059, Bureau of Mines, 1931, pp. 30-32.

[59] Heithecker, R. E., Some Methods of Separating Oil and Water in West Texas Fields, and the Disposal of Oil-Field Brines in the Hendricks Oil Field, Texas: Rept. of Investigations 3173, Bureau of Mines, 1932, 16 pp.

In the opinion of the Bureau of Mines, every salt-water disposal project is a self-contained problem covered by certain governing principles, the solution of which demands the cooperation of all interested parties.

Attention has been given also to the recovery of commercially valuable salts of iodine, bromine, and of other of the rarer elements in the hope of finding ways of obtaining these salts in such quantities as to convert a present waste into an economic asset.

Hard Facing Metals for Oil-Well Tools

During the past few years rapid development has been made in the drilling of deep wells. Where a few years ago a well that was 5,000 feet deep was considered an outstanding engineering achievement, at the present time depths of 10,000 feet are being obtained. While this increased drilling depth has been due in large measure to improvements in the construction of drilling rigs, rig irons, and other equipment, it has also been made possible by the development of hard-facing metals for oil-well tools. The ability to construct bits that will stand up for relatively long periods of time, when drilling through hard flinty formations, has greatly reduced the time and consequently the cost, of drilling operations. Engineers of the San Francisco office are now collecting data on this subject with particular reference to the types of metals used for hard facing, the methods of applying the material, and the reduced costs of drilling because of their use.

Safety Engineering in the Petroleum Industry

One of the primary reasons for the organization of the Bureau of Mines was to reduce the number and severity of accidents in the mineral industries. In the petroleum and natural-gas division, accident-prevention work has been carried on actively as an integral part of its other engineering studies. The Bureau has long maintained that accident prevention should be dealt with on a scientific basis, and although only two engineers of the Bureau are definitely assigned to studies of accident prevention in the petroleum industry at any one time, the individual work of these two men does not adequately represent the Bureau's activities in studying methods to prevent personal injury and loss of property. The experience of the whole Bureau of Mines stands back of the active work and technical writing of these two engineers.

A complete article in itself would be required to outline the activities of the Bureau of Mines on petroleum safety. Exclusive of special articles, some 80 reports dealing with petroleum safety and health, including fires and explosions, have been published by the Bureau and are available to the public. Some of these writings date back to 1913, but in 1923 two petroleum engineers were assigned to work on safety problems in order that they might collect and analyze statistical data on accidents and with this knowledge, theretofore unavailable, make engineering studies where the highest frequency and severity rates existed. Drilling and production problems were the first to be studied with the view of suggesting remedies for unsafe conditions. Natural-gasoline plants have had their share of attention, and a report has been published.[60]

Some recent technical work on safety problems deals with methods of reducing the hazards in the design and operation of petroleum cracking equipment at refineries, where the dangers from failure are greatly increased because of the corrosive effects of sulphur compounds (or erosive action) on equipment containing petroleum vapors that are subjected to high degrees of temperature and high-working pressure. A report is in preparation on this subject.[61]

When the hydrogen sulphide problem presented itself in west Texas and fields of the Permian Basin, the Bureau sent engineers and chemists to those areas in order to advise the oil companies and the men in their working places regarding the toxicity of this gas, with which so few were familiar, and to suggest remedial measures that would lessen the number of accidents from exposure to this gas, which in its poisonous effects is comparable with hydrogen cyanide. A report[62] was quickly prepared and followed by its sequel,[63] and both papers were given wide distribution throughout the industry.

Since the hydrogen sulphide studies of 1926 and 1927, a considerable amount of progress has been made, and methods have been developed by the industry and others that had not been recognized or that had not been proved at the time of reporting the earlier work. In order that there may be a general reference to the subject of hydrogen-sulphide poisoning and methods of preventing it in all departments of the petroleum and natural-gas industries, the Bureau has in preparation a technical paper which will bring this subject up to date.

One of the laboratory investigations on this work pertains to the pyrophoric characteristics of certain products of corrosion by hydrogen sulphide that have been known to ignite spontaneously and that present a hazard about which very little authentic information so far has been published.

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[60] Shea, G. B., Safety at Natural-gasoline Plants: Tech. Paper 462, Bureau of Mines, 1929, 109 pp.

[61] Marek, R. L., Safety at Petroleum Cracking Plants: Tech. Paper 551, Bureau of Mines (in press).

[62] Yant, W. P., and Fowler, H. C., Hydrogen Sulphide Poisoning in the Texas Panhandle, Big Lake, Tex., and McCamey, Tex., Oil Fields: Rept. of Investigations 2776, Bureau of Mines, 1926 (out of print).

[63] Fowler, H. C., Prevention of Hydrogen Sulphide Poisoning in Handling and Refining High-Sulphur Petroleums: Rept. of Investigations 2847, Bureau of Mines, 1927 (out of print).

The Bureau began giving first-aid instruction to the petroleum industry in 1920. At present there is hardly a person employed in the petroleum and natural-gas industries who is not familiar with the care of injured persons in case of an emergency. Not all of these men actually have been trained by the Bureau of Mines because the task of actually giving the instruction has become too great. The Bureau has sometimes been criticized for not making more trainers available, but funds for this work are definitely limited. If key men in any organization receive instruction in the application of first-aid methods, the company should be in a position to carry on its own first-aid instruction under the supervision of the Bureau of Mines, whose trainers hold examinations for Bureau of Mines first-aid certificates. First-aid training has been a large factor in accident-prevention work. The relationship of these two subjects is so thoroughly understood that it need not be elaborated upon here.

Petroleum Bibliography

The Bureau has compiled a bibliography of petroleum and allied substances since 1915. At first these bibliographies were published as annual bulletins of the Bureau of Mines. The amount of technical writing on oil and gas subjects has expanded rapidly, and the task of abstracting the articles became too great for one bibliographer to handle. Accordingly, through the cooperation of the Special Libraries Association and the endorsement of the American Petroleum Institute, this work was put on a cooperative basis as of January 1929.

Since that time "Recent Articles on Petroleum and Allied Substances" has been published monthly at the San Francisco petroleum field office in the form of 50 or more mimeographed pages. Until recently the bibliography has been mailed without charge to anyone requesting the service. The list contained approximately 560 names. However, in accordance with recent legislation, this publication has been put on a subscription basis, and the money derived therefrom is placed in the United States Treasury and not applied on the cost of printing. It appears that under existing conditions, the Bureau cannot long continue the publication of this work, in spite of the splendid assistance given by various technical librarians of oil companies and others.

This bibliography, placing in available form the carefully prepared abstracts of substantially all articles published in this and foreign countries on petroleum and allied substances, should be continued under some plan, but because of lack of funds, the Bureau feels that the cost of maintenance of this service must be assumed by the industry, or the work stopped.

Availability of Bureau of Mines Data on Petroleum and Natural Gas

Upon occasion the statement has been made that the Bureau holds back too many of its data at times when there is greatest need for them. The Bureau has endeavored always to make the information on a given subject available as soon as that information is properly authenticated within its own organization, provided no other circumstance is a controlling factor -- as, for example, certain confidential requirements. (Information made available to the Bureau of Mines from an outside source and specified "confidential" is meticulously treated as such until the donor of the information in question removes the confidential restriction.)

The Bureau of Mines is necessarily conservative in this matter because it realizes that too frequently conclusions are drawn without substantiating proof, and the general practice is followed that it is better to withhold a publication until the facts are established than to issue reports suggesting certain possibilities which, upon further investigation, may have to be modified. Wherever conditions will permit, especially where data are informative, rather than basic in nature, "short-time" reports are issued, interspersed between the longer reports on major projects.

CONCLUSION

The studies of the United States Bureau of Mines on petroleum chemistry and refining, production of oil and gas, pipe-line transportation of natural gas, engineering field studies, and special engineering problems, concerning which some general results have been given in this paper, by no means make up a complete list of technical research projects on oil and natural gas. Some years ago the Bureau was asked to compile a list of petroleum and natural-gas problems on which information was needed by the industry and on which the Bureau, in line with its function as a Federal research agency, could do work advantageously if funds were available. The number of problems which finally remained on the list after careful scrutiny was 106. No doubt this number would be increased if a similar tabulation were made today.

However, it is not the objective of the Bureau of Mines to see how many problems it might study, but rather to put into usable form the best obtainable information on the principal oil and gas problems, which, as a Federal agency, it is peculiarly fitted to study and make reports on for the improvement of methods of rational conservation of oil and gas and for the betterment of the social economy of the country.

The statement has been made that research in the oil and gas industry has been carried so far that the knowledge now available is acting as a deterrent rather than a help toward stabilization of economic conditions. It is true that engineering advancement in general has added to the complexity of many economic problems, but the statements regarding the detrimental effects of research are made by persons who fail to recognize the fact that good engineering is synonomous with sound economic principles.

Industry, largely through its own efforts, has come to accept the fundamentals of oil and gas conservation and safe operation - suggested, endorsed, and worked for by the Bureau of Mines since its organization. The judiciary of the country is coming to consider the conservation of oil and gas and rational methods of preventing waste, both physical and economic, in a different light than it did in the earlier years of the industry. The public at times has been inclined to criticize industry and perhaps has failed to understand the significance of technical research.

The true public interest is broader than the knowledge of the present retail price of gasoline. The public must know more about the fundamental concepts of recovery and utilization of oil and gas - not concerning itself so much with the detailed findings and interpretations of specific data - but it must appreciate how oil and gas and its orderly development and economic distribution to the consumer effect each individual socially and economically. The public must know, for example, something of the relationships of the oil-gas-energy attributes of a reservoir as they affect the correlative rights of all parties interested in the land. It must have some knowledge, also, of why it is necessary for technicians to study the characteristics of motor fuels and lubricants in order that more suitable grades of these products may be made available to meet the requirements of its automobiles, even though the actual technique is obscure to many individuals. It must recognize that national physical wastes attending production and manufacture cannot be changed into national assets in a short space of time.

Oil and gas conservation and its effect upon the social economy are extremely complex. The action of no one organization or group of organizations can cope with the situation. Progress results from the combined efforts of all forward-looking groups who are trying honestly to reach a definite objective.

Well-informed persons who have had an opportunity to study the work of the Bureau of Mines have stated that the bureau has selected types of work on general problems which the industry itself usually is not in a position to do, either in its own company research organizations, commercial research organizations, or in schools and colleges. They have stated also that the work of the Bureau, although under different conditions, is continuing as it did in former years to exercise a very definite influence in preventing waste and in conserving the natural resources of oil and gas.

The Bureau of Mines as a Federal agency has maintained its fore rank position as a research organization, studying oil and gas problems, through carefully guarding against premature judgment; its findings are based on fact, insofar as pertinent facts can be determined through experimentation and investigation; its conclusions are given without prejudice of property lines or viewpoint engendered by commercial affiliation. After severe criticism within the Bureau, most of the manuscripts are sent to nationally recognized authorities in the oil and gas industries for critical review and suggestion regarding presentation of the facts. Upon final approval and release, the findings on any subject are made equally available to large and small companies, individual operators, regulatory agencies, landowners, and the public.

With these precepts before it, and shunning mediocrity, the Bureau of Mines has been able, in the face of an increasingly complex social economy, to continue its proper function of developing the philosophy of research projects of national scope that pertain to oil and gas.